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Review Article

Insect as a promising food source: implications for sustainable consumption across species. a review

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ABSTRACT

Insects provide a crucial source of nutrients for human beings and many other animal species. Several insects, such as black soldier flies, house crickets, fruit flies, house flies, and mealworms, play crucial roles in providing essential micronutrients. Processing can transform insects into different formats, including pastes, powders, and meals. Edible insects (black soldier fly, crickets) have their potential to be farmed by using organic food waste, including manure, compost, and vegetable scraps unsuitable for individual consumption. Eating insects appears to have a lower environmental impact in relation to climate change compared to raising cattle, pigs, or chickens. Consuming insects appears to offer a sustainable solution for fulfilling the nutritional needs of our expanding global community. To better comprehend the potential socio-economic advantages of insect gathering and farming, further investigation is necessary to determine how these practices can improve food security in low-income contexts. Insects appear to raise minimal concerns regarding animal welfare, though the extent to which they may experience discomfort and pain remains unclear.

Keywords: Edible insects; protein-rich source; cultural acceptance; environmental impact.

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INTRODUCTION

Insects have held a significant role in the dietary record of humans across Asia, Europe, Africa, and Latin America. There are more than 1900 insect species globally that have been identified as a part of human nutrition. Among these, notable groups consist of locusts, caterpillars, beetle grubs, cicadas, winged termites, bees, grasshoppers, worms, ant offspring, and various types of aquatic insects (Figure 1) (Bernard & Womeni, 2017). It is fascinating to note that over two billion individuals regularly incorporate insects into their diets, and insect consumption contributes significantly to the intake of animal proteins in certain areas. Given the widespread practice of entomophagy and its favorable comparison with conventional livestock rearing in terms of nourishing content and ecological impact, it holds the potential to majorly alleviate under nourishment among the growing global population (Van Huis et al., 2013).

Insects' global population will grow by 25% in the coming decades, surpassing 9 billion (Millington & Cleland, 2017). As a result, an inevitable need to enhance food production will arise, compounded by complicating factors like climate change (Ksenija, 2018). The stability of entire food systems could face threats due to climate change-induced fluctuations in supply. Although the specific effects might not be fully evident at regional levels, shifts in climate patterns will probably worsen food insecurity in regions already prone to hunger and malnutrition (Ban, 2012). A potential requirement for increasing insect food production is as much as 70%, and this demand is especially pronounced for protein sources (Hunter et al., 2017). A pressing imperative exists to enhance the nutritional value of diets globally, ensuring an adequate supply of essential nutrients. Simultaneously, it is crucial to avoid exacerbating the worldwide surge in obesity and its associated chronic ailments such as cardiovascular disorders, gastrointestinal cancers, and diabetes (Organization, 2019; Williams et al., 2016).

The rise in global population is projected to lead to a roughly 50% surge in the demand for agricultural goods by 2030 (Coulter, 2004). This situation necessitates a transition toward the Eco-friendly amplification of nourishment frameworks (Garnett et al., 2013). The ramifications of climate change will introduce various changes to the global food scenario, affecting supply and demand. This will also impact food systems at the grassroots level, where small farming communities frequently rely on local resources and their cultivation (Nelson et al., 2012). Moreover, livestock farming holds significant economic and social advantages for numerous communities. Consequently, while consumers in wealthier, industrialized nations may progressively seek non-animal-based food alternatives, a requirement exists to enhance the sustainability of livestock cultivation in less affluent countries experiencing rapid population growth. This includes the exploration of non-human-edible feed components. The growing desire for meat and limited land resources drive the exploration of substitute protein sources. Insects have emerged as a viable option because of their smaller land needs and reduced ecological footprint compared to meat. Alongside their considerable nutritional value, insects also offer health advantages. Various edible insect species can be cultivated using organic byproducts, contributing to a circular economy. In recent times, insects have garnered growing interest as potential sources of both animal feed and human food components (Van Huis, 2016). Insects are often recognized as abundant reservoirs of vital nutrients, capable of thriving on less valuable feed sources while maintaining a minimal carbon footprint (Gasco et al., 2020; Van Huis et al., 2013).

Insects have been a dietary staple for centuries (Raheem et al., 2019). While insect consumption might not be embraced in many regions, around 2000 species of insects are fit for consumption, having been part of the diets of diverse ethnic communities (Ghosh et al., 2017; Ramos-Elorduy, 2009). Consumable insects have gained acknowledgment for their exceptional nourishing content and potential to provide more economically viable prospects (Bae & Choi, 2021; Gasco et al., 2020; Han et al., 2017). Insects represent sustainable food options to meet the escalating future food requirements, appealing to the broader public based on scientific merits. Insect consumption is widely acknowledged for their considerable economic, nourishment, and flavor-related merits. Furthermore, these insects demand fewer resources and demonstrate remarkable conversion rates, along with exceptional reproductive capabilities all year round (Bae & Choi, 2021; Gamborg et al., 2018; Megido et al., 2016; Van Huis et al., 2013).

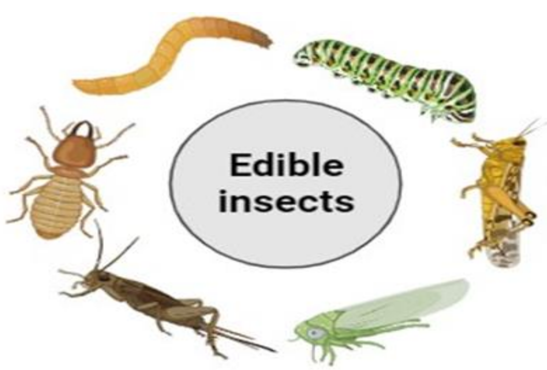

Figure 1. Insects as a promising food source for animals and humans.

Nutritional Content of Insects

Insects play a crucial role as nutrient sources for other animals and humans. Numerous insects, such as house crickets, fruit flies, and house flies, are valuable suppliers of essential micronutrients such as zinc, iron, and B vitamins (Raheem et al., 2019). Processing could transform insects into different formats, including pastes, powders, and meals. This

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extends their shelf life and enables convenient incorporation as alternatives in culinary and baking endeavors, often without significantly altering the prepared dish's flavor, appearance, or texture (Dossey et al., 2016). Besides their essential role in global diets, insects offer the possibility to be a more eco-friendly, responsible, and enduring alternative for human nourishment compared to other commonly ingested sources derived from animals (Fellows et al., 2014). Insects exhibit significantly higher efficiency in feed, as they can transform their feed into edible food more effectively than other animals (Oonincx et al., 2015).

Insects as Nutritious Food: Macro and Micronutrient Source for Humans

Insects are recognized as abundant reservoirs of vitamins, protein, and fat. Nevertheless, their nutritional worth fluctuates based on diet, life stage, gender, species, growth conditions, and assessment techniques (Van Huis & Oonincx, 2017). Typically, the protein content of consumable insect's spans from 35 to 60 percent of weight after drying or 10 to 25 percent of fresh weight. At the higher end of this range, it can be comparable to protein from other animal sources (Melo et al., 2011; Schlüter et al., 2017). Fat is the second most significant element in the nutritional makeup of insects (Mlček et al., 2014). Numerous factors, such as reproductive phase, species, diet, gender, habitat, and season (individually or combined), can potentially impact the fat content of insects (Schlüter et al., 2017). Coleoptera (grubs and beetles), Isoptera (termites), Orthoptera (Cricket, grasshoppers, and locusts), Lepidoptera (caterpillars), and Blattodea (cockroaches) exhibit average fat contents (13.41%, 27.66%, 29.90%, 32.74%, and 33.40%) weight after drying (Rumpold & Schlüter, 2013). As a general trend, pupae and larvae tend to contain more fat than adult insects (Mlček et al., 2014). Additionally, fatty acid composition in insects is influenced by the specific species and their dietary habits (Schlüter et al., 2017). Nevertheless, insects typically exhibit a lower presence of saturated fatty acids (SFA) in comparison to unsaturated fatty acids (UFA) (Castro et al., 2018).

Carbohydrates within insects predominantly take two forms: chitin and glycogen. Chitin, an N-Acetyl-D-glucosamine polymer, constitutes the exoskeleton's primary component, whereas glycogen functions as a stored energy reserve within muscle tissue and cells. The carbohydrate content of edible insects varies on average from 6.71% (stink bug) to 15.98% (cicada) (Mlček et al., 2014). Chitin has been identified for its antioxidant properties (Jung and Zhao, 2012), as well as its potential in activities such as combating tumors and microbes (Ibañez-Peinado et al., 2020; Younes et al., 2014), thereby holding diverse applications across multiple sectors (Morin-Crini et al., 2019). Macronutrients: certain insects (such as grasshoppers, crickets, termites, and mealworms) contain essential minerals like calcium, iron, phosphorus, zinc, copper, manganese, and magnesium. Invertebrates without a rigid skeleton typically have low calcium content (de Castro et al., 2018; Mlček et al., 2014). While most consumable insects display iron levels akin to meat, exploring mineral bioavailability in insects remains an area that requires further investigation (Castro et al., 2018; Mwangi et al., 2018). Examinations into the vitamin content and bioavailability of edible insects remain inadequate. The data suggest that edible insects encompass carotene, vitamins B1, B2, B6, C, D, E, and K (Mlček et al., 2014). Specifically, Folic acid sources are Coleoptera and Orthoptera (Rumpold & Schlüter, 2013).

Amino acids and Protein

Insect's protein composition ranges from 25 to 75 percent based on dried material measurements (Finke, 2013, 2015; Oonincx & Dierenfeld, 2012). The amino acids composing genuine protein are generally categorized into nutritionally dispensable and essential amino acids. Although each amino acid is essential and nutritionally indispensable, it cannot be produced by most animals and, therefore, supplied through their food. Differences in amino acid profiles during various phases of a specie's life are influenced in part by whether the species experiences complete developmental stages (holometabolous) like butterflies, beetles, and flies or incomplete metamorphosis (hemimetabolous) such as grasshoppers, cockroaches, and dragonflies (Finke, 2002; Pieterse & Pretorius, 2013). Protein's quality is also influenced by its digestibility, affecting amino acid availability. Insect-based meals derived amino acids that are easily accessible to poultry, offering values equivalent to or even surpassing those found in traditional protein sources like fish or soybean meal. The sole exception lies in BSF larvae meal, which exhibits minimum digestibility of amino acids, particularly those containing sulfur, such as methionine and cysteine (De Marco et al., 2015; Schiavone et al., 2017).

Fatty acid composition

The insect's Fatty acid makeup depends on variables like species, life phases, and environmental elements like temperature, light, and diet (Finke & Oonincx, 2017; Thompson, 1973). Generally, males of various species (e.g., Crickets and mealworms) possess smaller fat reserves than female insect species (Lease & Wolf, 2011; Liu et al., 2017). Insects captured from the wild typically exhibit substantial quantities of linoleic acid (18:3 n-3) and linoleic acid (18:2 n-6) (Ekpo & Onigbinde, 2007; Thompson, 1973). Conversely, insects raised commercially tend to have higher concentrations of linoleic acid and significantly reduced levels of alpha-linolenic acid compared to their untamed counterparts. This discrepancy arises from their diet, which often consists of significant grain by-products characterized by lower linoleic acid content. Black soldier fly larvae possess a distinctive fatty acid composition abundant in lauric acid, a trait that remains consistent regardless of their dietary intake (Dreassi et al., 2017; Oonincx et al., 2020).

Minerals

Minerals can be categorized into two groups: macro-minerals, which include sodium, chloride, potassium, calcium, magnesium, and phosphorus, and micro-minerals, which include copper, iron, manganese, zinc, selenium, and iodine. The categorization is determined by the quantity required to fulfill their diet needs. In most species, macro-mineral needs are expressed in grams per kilogram (g/kg), while micro-mineral requirements are specified in milligrams per kilogram (mg/kg). Most insect's exhibit significantly elevated levels of microminerals such as manganese, iron, copper, zinc, and selenium. These levels are typically adequate to fulfill the dietary needs of most animals (Finke, 2013; Oonincx & Dierenfeld, 2012). Fully developed fruit flies (Drosophila melanogaster) and house flies possess notably elevated concentrations of iron (ranging from 125 to 454 mg/kg dry matter). This iron content is comparatively higher than that found in the majority of other insect species (Finke, 2013)

Vitamins

The vitamin content in edible insects can vary depending on several elements, such as the insect species, feed, and developmental stage (Table 1).

Table 1. Importance of vitamins present in different insect species.

Sr.	Vitamins	Compounds	Insects	Importance	References
1.	Vitamin A	Retinoid and carotenoids	Butterfly caterpillars, such as the species (*Imbrasia oyemensis*, and *Nudaurelia)*, and House cricket	The calculated values for Vitamin A are expressed as 1 unit (U) equivalent to 0.3 micrograms of retinol. β-carotene and Retinol were detected in some butterfly caterpillars containing 32–48 µg retinol and 6.8–8.2 µg β-carotene per 100 g dry matter	(Barker et al., 1998; Dobermann et al., 2017; Payne et al., 2016)(Gahukar, 2020)
2.	Vitamin B	Cobalamin, Riboflavin, and thiamin	House crickets, larvae of mealworm (*Tenebrio. molitor*)	Riboflavin is represented in Consumable insects ranged from (0.11 to 8.9 mg/100 g). Cobalamin is found in abundance in yellow beetle *T. molitor* larvae (0.47 µg per 100 g) and crickets *A. domesticus* (5.4 µg per 100 g in adults, 8.7 µg per 100 g in nymphs).	(Chen et al., 2009; Kinyuru et al., 2015; Payne et al., 2016; Vangsoe et al., 2018) (Gahukar, 2020)
3.	Vitamin E	Tocopherols and tocotrienols	House crickets, Larvae of yellow mealworm, and black soldier fly	For house crickets, the vitamin E content ranges from (8 to 195 IU/kg) of dry matter, while for yellow mealworm larvae. Larvae of Black soldier fly display a range of (10 to 235) IU/kg.	(Barker et al., 1998; Punzo, 2003) (Finke, 2002; Pennino et al., 1991)

4.	Vitamin D	cholecalciferol	Yellow mealworm larvae Black soldier fly larvae, and Termites (*Macrotermes annandalei*)	The termites exhibit a vitamin content of 2500 IU per 100 grams, while vitamin D attains an 8540 IU per 100 grams. There is no indication of de-novo synthesis in BSF larvae, whereas larvae of yellow mealworm can achieve levels exceeding (6,000 IU) per kilogram of dry matter	(Kouřimská & Adámková, 2016) (Oonincx et al., 2018)

Environmental Benefits of Consuming Insects as Food

Environmental benefits of producing and consuming insects are linked to their notably high conversion rate from feed to meat. Insects are remarkably efficient in transforming plant proteins into insect proteins, surpassing the efficiency of other animals in this regard (Deroy et al., 2015). In order to gain one kilogram of body weight, crickets require less than two kilograms of feed. In contrast, chickens, pigs, and cows have higher feed requirements. On average, chickens need 2.5 kilograms of feed, pigs require 5 kilograms, and cows require up to 10 kilograms of feed to achieve the same one-kilogram increase in body weight (Collavo et al., 2005; Smil, 2002). Another benefit of using insects as a sustainable protein option is the substantial proportion of suitable creatures for consumption. As much as 80 percent of a cricket's body is edible, compared to 55 percent for chickens and pigs and 40 percent for cattle (Nakagaki & Defoliart, 1991).

Regarding sustainability, a significant benefit of consumable insects (black soldier fly, crickets) is their potential to be farmed using organic food waste, including manure, vegetable scraps, or compost, which are unsuitable for human consumption. This method holds promise for lessening environmental pollution. Utilizing food waste to raise insects presents an appealing strategy for completing the food chain cycle within a sustainable circular economy (Ojha et al., 2020). Employing organic byproducts as food sources for insects can enhance the profitability of insect farming operations (Offenberg, 2011). Nevertheless, employing such waste might lead to lower nutrient efficiency and decreased growth (Smetana et al., 2016). Furthermore, using organic byproducts as food sources could potentially elevate mortality rates among crickets (Lundy & Parrella, 2015).

Insect consumption seems to be environmentally friendly regarding climate impact compared to chickens, pigs, and cattle. The lower space and water requirements for the growth and development of insects and their reduced contribution to greenhouse gas emissions make them a more sustainable and environmentally friendly protein source than traditional livestock. The current methods of agricultural outputs are progressively linked to environmental decline, deforestation, and increased greenhouse gas emissions. Massive facilities dedicated to livestock and fish production impose substantial environmental burdens (Fiala, 2008; Tilman et al., 2002). Among these, land usage emerges as a pivotal concern. Livestock rearing, responsible for more than 70 percent of global farmland utilization (Food and Agriculture Organization of the United Nations, 2009), will progressively compound environmental challenges. As climate change reduces available agricultural land, this trend worsens food insecurity (Lloyd et al., 2011; Premalatha et al., 2011).

Continuously growing pressure on water resources will jeopardize agricultural yield and global biodiversity, impacting agricultural outputs. Agricultural activities consume as much as 70% of the world's freshwater (Pimentel et al., 2004), with meat production incredibly demanding significant water resources. The water quantity needed to produce 1 kilogram of meat requires approximately 2,300 liters of water for chicken, 3,500 liters for pork, and a staggering range of 22,000 to 43,000 liters for beef (Chapagain & Hoekstra, 2003; Pimentel et al., 2004). The water requirement for generating 1 kilogram of consumable insects is believed to be notably reduced (Van Huis et al., 2013).

Livestock farming contributes to 18 percent of global greenhouse gas emissions, surpassing the emissions generated by the transportation sector (Steinfeld, 2006). Insects, in comparison, seem to release significantly lower quantities of ammonia and greenhouse gases compared to pigs or cattle. Farming edible insects has been observed to produce methane, carbon dioxide, and nitrous oxide emissions that are around 100 times lower per kilogram of weight than cattle (Oonincx et al., 2010). Urine and manure, which contain ammonia, are significant sources of environmental pollution in traditional livestock farming. These waste products can lead to nitrification and soil acidification, negatively impacting air and water quality (Aarnink et al., 1995). Regarding ammonia emissions, edible insects have a significant advantage over traditional livestock, such as pigs, with a difference of up to tenfold (Oonincx et al., 2010).

Implications for Human Consumption

Public health considerations and safety aspects of consuming insects

Primary risks currently linked to the consumption of insects as food include allergies, concerns about food safety related to microbes, and the presence of anti-nutrients in some insect species, which may hinder nutrient absorption in the human body (Fig 1, 2). However, under proper hygienic management practices, there is currently limited evidence to suggest that disease or parasitic transmission to humans occurs due to insect farming and consumption (Van Huis et al., 2013). Generally, insects recognized as consumable are deemed protected for consumption when they undergo proper processing and handling.

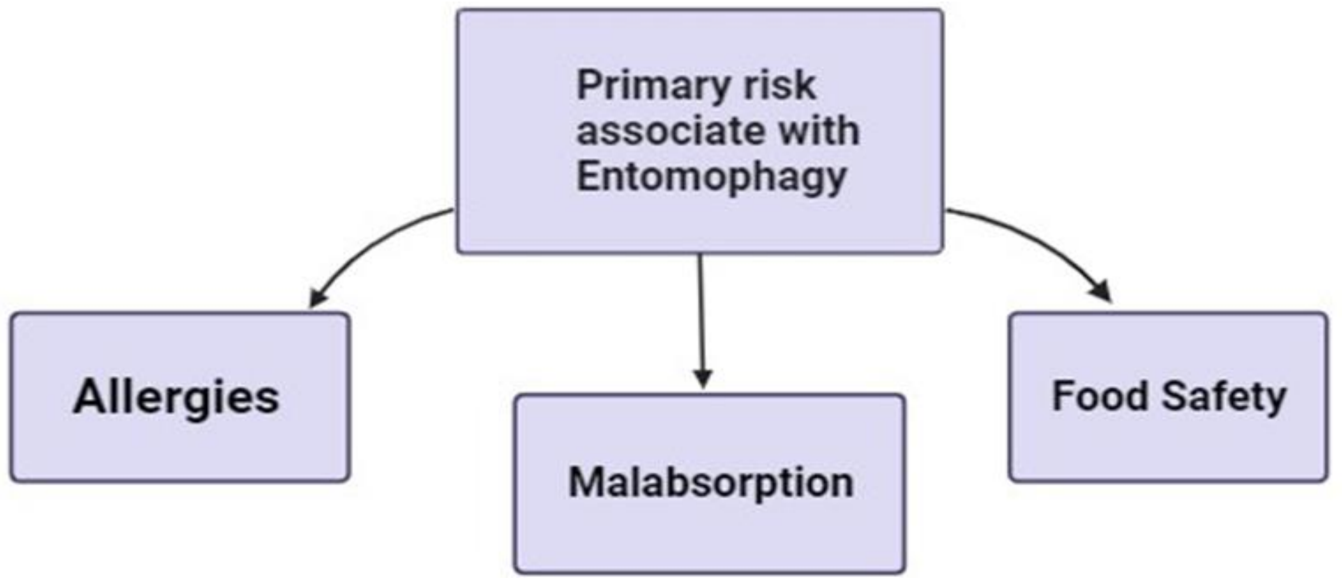

Figure 2. Primary risks associated with entomophagy include allergies, food safety, and malabsorption.

Allergies

Allergies resulting from insect consumption, cross-reacting proteins implicated in insect allergies, and potential changes in allergenicity due to processing and digestion can be found (de Gier & Verhoeckx, 2018). While examining potential health hazards associated with insect consumption (Testa et al., 2017). The allergenic effects of insect consumption can be challenging (Yates-Doerr, 2015). However, these effects have been identified to different extents. As insects belong to the arthropod family, they may cause mild allergic reactions in some individuals who consume them (Ayuso, 2011). There are several antigenic factors known to be shared among arthropods. The existence of cross-reacting between crustaceans and insect consumption has been confirmed (Belluco et al., 2013).

Furthermore, pan-arthropod allergens such as tropomyosin and arginine kinase are significant (Ribeiro et al., 2018). People who have allergies to shrimp may have a higher probability of being allergic to yellow mealworm than other insect species (Broekman et al., 2017). Additionally, serum from individuals with allergies to crustaceans and dust mites can react with mealworm proteins, indicating the possibility of cross-reactivity. This suggests that people allergic to dust mites may also be sensitive to insect proteins, including those found in mealworms (Verhoeckx et al., 2014). There is a substantial relationship between the levels of specific Immunoglobulin E (IgE) in two-spotted crickets, the levels of IgE reactive to shrimp, and their respective reactions (Kamemura et al., 2019). Crickets might provoke reactions from individuals with a crustacean allergy. While not common, severe reactions to edible insects can potentially lead to dangerous or even fatal cases of anaphylaxis. Instances of anaphylactic shock associated with entomophagy have been documented in rare cases (Ji et al., 2008; Okezie et al., 2010). It is a prudent suggestion to advise individuals who are already known to have allergies to shellfish or mollusks to steer clear of entomophagy (Testa et al., 2017). Additionally, those with occupational exposures that could lead to allergies, especially those who work closely with consumable insects, face a potential risk (Mlček et al., 2014). To validate and delve deeper into this subject, conducting food challenges, placebo-controlled trials, double-blind, and research on molecular mechanisms is essential.

Food safety

There is no indication consuming insects carries more significant health risks than other animal products (Mézes, 2018). Like all meat products, handling and processing insects is crucial to guarantee food safety. It is recommended to use heat treatments as a precaution to minimize hazards (Vandeweyer et al., 2018). Microbial contamination is a particular concern during certain insect production and distribution stages, such as storage, processing, and transportation. In specific circumstances, the microorganisms found in insects can create conditions that promote the proliferation of harmful microorganisms (like Enterobacteriaceae) (Klunder et al., 2012). Enterobacteriaceae is recognized for causing foodborne illnesses. Insects can become tainted due to mishandling and inadequate processing methods (Opara et al., 2012). Certain cooking methods may not completely eliminate bacterial spores (Ter Beek & Brul, 2010). Hence, it is imperative to consistently apply appropriate processing, handling, and storage procedures to effectively eliminate any pathogenic microorganisms on or within consumable insects, ensuring food protection (Klunder et al., 2012; Testa et al., 2017). Food safety can be compromised by the existence of toxins and chemical contaminations.

Edible insects are susceptible to contamination from pesticides in food sources, and certain species of insects may have toxins or repellents associated with their defense mechanisms (Rumpold & Schlüter, 2013). As an illustration, consuming fried insects can lead to histamine toxicity and poisoning. When bacteria decarboxylate the amino acid histidine, which is present in significant amounts in grasshoppers and silkworm pupae, they produce histamine. This heat-resistant toxin has the potential to result in symptoms such as skin diarrhea, rashes, chest tightness, nausea, headaches, vomiting, breathing difficulties, and other complications (Chomchai & Chomchai, 2018). Consumers should be cautious when eating the scarab beetle species *Eulepida mashona* Arrow, which belongs to the family Scarabaeidae and order Coleoptera that is found in Zimbabwe. It's worth noting that this beetle may still retain cyanogenic compounds even after being cooked using traditional methods (Musundire et al., 2016). Accumulation of heavy metals in many insects, such as grasshoppers, or the existence of mycotoxins like aflatoxin, could potentially present additional concerns (Banjo et al., 2010; Handley et al., 2007; Musundire et al., 2016).

Malabsorption

Certain insects such as ants, grasshoppers, and silkworms contain anti-nutrients like oxalate, tannin, saponins, phytate, alkaloids, and hydro-cyanide, which have the potential to influence and hinder the absorption of essential nutritional components (Chakravorty et al., 2016; Longvah et al., 2012; Musundire et al., 2014). For instance, phytic acids have the potential to function as chelators, thereby lowering the availability of minerals. Insects can obtain anti-nutrients in two ways either by absorbing them from the food they consume or by producing them internally. Consequently, the conditions under which the insects are raised could impact food protection. Processing and heating methods can influence the concentration of anti-nutrients and nutrient digestibility (El Hassan et al., 2008). Additionally, vitamins that are sensitive to heat may be affected during these processes (Williams et al., 2016).

Cultural Acceptance and Overcoming Psychological Barriers

Although entomophagy offers numerous advantages, the widespread acceptance of diets centered on insect feeding still represents a significant obstacle in Western countries. Insects are a regular component of many people's diets in numerous regions around the world, but in many Western countries, their consumption is often perceived as repulsive and linked to a less advanced or primitive way of life, as indicated by various sources (Hartmann & Siegrist, 2017; Rozin & Fallon, 1987; Vane-Wright, 1991). Furthermore, unlike many other parts of the world, insect consumption has not historically been a significant part of Western food culture. This unfamiliarity with insects as a food source may make some consumers hesitant to embrace them as a source of nutrition.

Disgusting feelings are crucial in an individual's reluctance to accept certain foods, as noted in various sources (Fessler & Navarrete, 2003). Culturally ingrained food practices deeply influence the source of the aversion towards consuming insects and the decision to accept or reject them as food (Mela, 1999; Mignon, 2002). Traditions and trends primarily shape People's dietary choices, and the reluctance to embrace entomophagy can be linked to preconceived biases (Bequaert, 1921). Whether entomophagy can integrate into Western dietary habits hinges on both the accessibility of edible insects and the ability to address and change the negative perceptions of insects. Several methods have been employed to persuade individuals that insects can be tasty, aiming to shape consumer preferences towards a positive perspective on insect as a viable diet option (Van Huis et al., 2013). These methods encompass educational showcases in zoos and museums, a blend of informative discussions, and firsthand insect-tasting experiences, with insects being introduced as edible items in "bug banquets" (Looy & Wood, 2006; Wood & Looy, 2000). The emergence of insect-based culinary creations, such as snacks and menus in bars and restaurants, along with the availability of cookbooks specifically focused on edible insects, is becoming more prevalent (Menzel & d'Aluisio, 1998). Empirical evidence has verified that "bug banquets" are effective in helping individuals overcome their aversion to consuming insects (Van Huis et al., 2013). Attitudes towards entomophagy vary across the globe, making it necessary to employ distinct communication strategies for promoting insect consumption in different regions. In areas where food security is precarious, there should be a push to promote edible insects as vital food sources due to their nutritional and economic benefits. Several regions where insect's consumption is deeply rooted in the culture, it's important to conserve and champion edible insects as a food resource to counter the impact of Western dietary patterns.

In developed nations, efforts to encourage insect consumption and products derived from insects must address and surpass the biases and feelings of disgust associated with them. Specifically, ensuring insects' safety as a food source can contribute to altering perceptions and fostering consumer acceptance in Western nations.

Education for Promoting Insect Consumption

Western individuals typically hold an unfavorable outlook on invertebrates. The consumption of insects as sustenance poses a potential challenge to our cultural and psychological identity (Looy et al., 2014). Nonetheless, there is a growing recognition that using insects as a source of animal feed and nourishment might be a practical substitute for the protein derived from traditional livestock species. The enthusiasm for this subject pertains to the ecological, dietary, and health advantages of these small-scale livestock, while all the consumption of insect-based products appears to be a secure choice. As part of our future food supply, insects could be incorporated into formal education.

Education of Insects as a Cultural Food

The traditional wisdom about the insect's consumption as animal feed and sustenance within the educational syllabi of African schools (Dzerefos & De Sousa, 2020). Bringing insect gatherers as guest speakers to schools allows them to impart their oral heritage and provide specialized on-site training to the younger generation (Shin et al., 2018). A vibrant comic tailored for South African children, featuring an edible stinkbug. The comic provides insights about these insects, offers guidance on creating an origami stinkbug, instructions on removing chemicals to make them suitable for consumption, and includes an engaging crossword puzzle (Dzerefos & De Sousa, 2020).

In the hilly regions of central Japan, residents hunt and consume the "hebo" wasp while also partially cultivating species of Vespula as a pastime (Nonaka & Yanagihara, 2020). Unfortunately, hunting hebo wasps has not been widely adopted by younger generations, who may have moved to urban areas for work opportunities. As a result, older adults are often the only ones who continue to engage in this activity. High schools of agriculture rose to the occasion and established a hebo club, where students are educated by their seniors on the art of locating, gathering, housing, and nurturing edible wasps.

Education of Insects as a Novel Diet

Consumable insects face limited acceptance among Western populations. Factors such as the absence of established traditions, unfamiliarity, legal constraints leading to limited availability, food aversion, and feelings of repulsion are significant barriers preventing edible insects from making inroads into Western markets (Hartmann & Siegrist, 2017). In Sweden, children aged 4 to 5 years old attend public pre-schools. The primary finding was that children's feelings spanned from inquisitiveness to anxiety. The ongoing struggle between aversion to the new and a fascination for the novel is a widely recognized phenomenon. Nevertheless, by beginning with the innate curiosity and imaginative nature of young children regarding insects as a dietary source, that is not only possible to boost awareness and stimulate a greater intrigue in insects as a food option (Nyberg et al., 2021).

In a town in England, there has been a trend of children between the ages of 8 and 10 consuming insects in schools (Tranter, 2013). Emphasizing the advantages for health and the environment appeared to be the most effective method for introducing insects as a diet source. They opted not to present the insects in their complete state; instead, they concealed them within cereal bars and chocolate products. Motivating children to engage all of their senses as they craft, examine, and discover is highly beneficial. This approach is referred to as sensory education or sensory-based learning. In Finland, a six-month educational program was implemented for children aged 8-12 to foster their willingness to try previously unexplored foods (Mustonen & Tuorila, 2010). Children in educational groups participated in a greater variety of novel diets than in the initial assessment. On the other hand, the group that did not receive any treatment or intervention did not exhibit any changes. The most significant reduction in food neo-phobia was achieved through the most rigorous educational efforts, particularly among the younger age group.

To overcome children's natural aversion to the unfamiliar, insects are being prepared as food to make them more appealing and acceptable to consume. Mealworm and Grasshopper were integrated into a conventional Danish treat (oatmeal balls). Although cooking activity did not impact the level of acceptance, the initial tasting was more positively received than the subsequent one, with the mealworm variation being favored over the grasshopper option (Chow et al., 2021).

The readiness of children and adolescents in Germany to partake in insect consumption and their findings revealed that older participants displayed a heightened inclination toward trying insect-based burgers (Dupont & Fiebelkorn, 2020). French adolescents aged 10 to 20 demonstrated that as young individuals grow older, they become more inclined to sample international cuisine, with puberty marking a significant turning point (Nu et al., 1996). The way insect-based products are presented, such as in the form of burgers, can be a powerful indicator of people's willingness to try them, highlighting the importance of effective marketing and educational initiatives to promote their acceptance (Dupont & Fiebelkorn, 2020).

An experiential teaching program for university students features a tasting session to foster favorable encounters with consumable insects, underscore the benefits of insect farming, and diminish the novelty associated with consuming insects. They noted that a more favorable view of insect feeding was positively correlated with greater exposure to insect consumption and increased knowledge about them (Petersen et al., 2020).

5. Implications for Animal Consumption

The discernment of avant-garde protein reservoirs suitable for incorporation into animal rations might liberate conventional protein reservoirs to sustain the human populace. Arthropods harbor indispensable amino acids and bioactive constituents that have the potential to exert a favorable influence on the intestinal microbial milieu and the general well-being of fauna (Bovera et al., 2016; Smola et al., 2023). Black Soldier Fly (*Hermetia illucens*), and Mealworm (*Tenebrio molitor)*, stand as viable entomological selections for integration into livestock rations.

Conspicuously, in the context of swine and aquatic organisms, the utilization of entomophagous sustenance augments the abundance and heterogeneity of microbial taxa within the intestinal tract, thereby fostering the proliferation of commensal microflora. Furthermore, the incidence of pathogenic agents exhibited a reduction, plausibly attributed to the antimicrobial attributes inherent in feeds derived from insects. Conversely, when juxtaposed with porcine and piscine counterparts, it becomes apparent that avian species may only accommodate rations incorporating insect-based constituents at more modest inclusion levels.

5.1 Insect-based diets for livestock, poultry, and aquaculture

Supplementing poultry regimens with insect-derived meals may yield improved growth rates and heightened feed utilization effectiveness, thereby insinuating their feasibility as cost-effective and efficient protein reservoirs for avian nourishment. Moreover, studies have shown that incorporating insect-derived diets into poultry rations reduces ecological footprint when contrasted with orthodox protein origins (Salomone et al., 2017; Schmitt & de Vries, 2020; Van Huis, 2022). Insects present themselves as a dependable and copious protein reservoir for livestock husbandry and aquaculture domains. Insects inherently serve as an innate protein source for piscine and avian populations (Leiber et al., 2017).

The nutritive worth of insect-based meals as innovative protein reservoirs within animal rations signifies their consideration as a compelling and enduring remedy. Insect meal presents itself as a prospective substitute for fish meal, a feed component that frequently becomes scarce, notably within the perpetually expanding domain of aquaculture (Mariod, 2020; Van Huis, 2022). Insect-derived sustenance might establish a market niche akin to that of soybean meal (SBM) and fish meal, which presently stand as the most substantial constituents in the formulation of feed materials for both aquaculture and animal nutrition (Allegretti et al., 2018; Di Mattia et al., 2019). Furthermore, it is imperative to scrutinize the extant statutes and regulatory frameworks to ascertain that including these diminutive organisms in livestock nourishment complies with legal provisions.

Within emerging economies, a pressing impetus exists to elevate meat consumption and stimulate the assimilation of alternative protein components into the domain of animal sustenance. Insects are surging in prominence as advantageous protein substitutes within animal rations, owing to the exceptional nutritional content of numerous insect varieties. Incorporating insects into animal feed supplies can help lessen the environmental impact associated with feed production, providing a more sustainable and eco-friendly solution (DeFoliart, 2012; Dörper et al., 2021).

Vitro breakdown of organic matter (OM) and protein in housefly's pupae demonstrated equivalence in fish and poultry-based meals. Earlier this year, the United Nations Food Agency formally designated house flies, mealworms, silkworms, and black soldier flies as the most adept organisms for the industrial production of animal feeds. According to the FAO, roughly 60-70% of the overall expenditure pertains to protein resources, encompassing meat, fish, and soybean feed. Protein compounds extracted from the Black Soldier Fly (BSF) can benefit both pets and aquatic animals, contributing to their overall health and well-being. The process of aging constitutes a noteworthy impediment for livestock. As animals age, the accumulation of harmful free radicals in their bodies can accelerate, potentially leading to various health problems.

In the European context, the utilization of insect-derived proteins within livestock rations is witnessing a burgeoning surge in prominence (Ismail et al., 2020). Protein resources derived from insects are particularly well-suited for the nourishment of juvenile animals, as they undergo rapid growth and can fortify their immune systems. A protein extract derived from the Black Soldier Fly may be able to mitigate the extent of free radical-induced harm within the physiological systems of livestock.

Conversely, aquatic organisms often exhibit susceptibility to contamination induced by harmful bacteria, culminating in a spectrum of health challenges, including compromised immune functions, hastened aging, and a medley of detrimental consequences (Lieke et al., 2020). Precision nutrition represents a strategic methodology crafted to attain the utmost alignment between requisite nutrients for animal feed synthesis and peak performance. This strategy enhances economic efficiency throughout production, concurrently curtailing wastage and mitigating environmental repercussions. Insect-based dietary regimens have been introduced into the marketplace to elevate feed quality and digestibility to enhance the overall productivity of animals. Simultaneously, these diets aim to ameliorate the efficient utilization of nutrients and enhance safety and sanitary standards within the poultry industry (Cheng et al., 2019; Imsland et al., 2018).

Nutritional Benefits and Potential Improvements in Animal Welfare

The budget allocation for livestock industry expenditure entails a substantial share, ranging from 60% to 75%, with the protein component constituting more than 15 percent of the comprehensive diet cost (Khan et al., 2016). Various protein-rich feed origins, including legumes, grains, and animal byproducts, traditionally comprise integral constituents within high-quality rations. Within the environmentally conscientious sector, there is a mounting enthusiasm regarding using insects as a protein reservoir within the ambit of livestock nutrition (Van Huis et al., 2013). Hence, it is pragmatic to consider insect cultivation at a magnitude commensurate with demand, utilizing them as a viable substitute component to foster sustainability within the livestock sector (Veldkamp et al., 2012). Insects are among the prospective commodity substitutions as novel protein reservoirs for the formulation of animal dietary materials (Makkar et al., 2014; Sánchez-Muros et al., 2014). It can be employed as a substitute or means to curtail the utilization of other costly and premium-grade feeds, including fish meal, soybean meal, oil, meat bone meal, and casein. Silkworm (*Bombyx mori*), Black Soldier Fly (*Hermetia illucens*), and Cricket (*Gryllus bimaculatus*) larvae emerge as prospective insects that could be harnessed as both animal diet and nourishment (Table, 2).

Environmental Impact and Sustainability of Insect-Derived Livestock Feed

Production of insects, whether intended for consumption or inclusion in animal feeds, exerts a discernible influence on the biosphere. The influence can be categorized into both direct and indirect ramifications. For instance, as a consequence of the respiration and metabolic activities of these insects, along with the discharge of their excrement, emissions of nitrous oxide (N2O), methane (CH4), carbon dioxide (CO2), and ammonia (NH3) can occur. It's worth noting that direct emission measurements have only been quantified for a limited set of five insect species. Nonetheless, these emission levels appear to register lower when juxtaposed with those observed in conventional livestock (Oonincx et al., 2010).

Mealworms, employed as a high-protein sustenance source, can be analogized to animal flesh and lacteal derivatives. As protein-dense nutritional constituents, BSF and houseflies equated to piscine repast and leguminous rations. These investigations exemplify that the energy consumption in insect cultivation setups exceeds established standards. The generation of fodder represents a paramount catalyst for environmental repercussions within conventional animal husbandry systems, and the domain of insect cultivation systems does not deviate from this trend. This becomes patently evident when scrutinizing land utilization; for instance, the manufacturing facility dedicated to mealworms was connected to a mere 0.2% of the overall land usage, while the sustenance allocated for the said facility was linked to an overwhelming 99 percent of land occupation usage (Oonincx & De Boer, 2012). Likewise, the immediate water consumption of said establishment constituted a mere fraction of the aqueous resources, encompassing rainfall, mandated to create sustenance. In contrast to the poultry domain, obtaining one gram of consumable protein demands two to threefold the expanse of territory and 50% additional water when juxtaposed with the procurement of mealworms (Miglietta et al., 2015; Oonincx & De Boer, 2012).

Table 2. Nutritional benefits and potential improvements in animal welfare.

Sr.	Nutritional aspects	Black soldier fly (BSF)	Cricket	Silkworm	Reference
1.	Crude Protein	42% - 54.09%	54.10%	51.1%	(Harlystiarini et al., 2019; Kroeckel et al., 2012) (Jayanegara et al., 2017) (Pereira et al., 2003)
2.	Fat Content	11.8% - 34.8%	26.90%	34.4%	(Astuti et al., 2018) (Jayanegara et al., 2017) (Pereira et al., 2003)
3.	Amino Acid	Rich in glutamic acid (3.49%)	Essential and nonessential (e.g., 8.13% alanine, 13.00% glutamine, 6.36% glycine, and 6.90% arginine)	Essential amino acids (e.g., linolenic acid 24.4% linoleic acid 8.57%,)	(Astuti et al., 2018). (Jayanegara et al., 2017) (Osimani et al., 2017) (Pereira et al., 2003)
4.	Fatty Acid	Lauric acid 40.29%, while linoleic 4.02%, oleic 7.99%, and palmitic acid 9.99%,	Palmitic acid (50.32%), stearic acid (32.06%), oleic acid (9.77%), linoleic acid (2.34%)	Balanced omega-3 and omega-6 fatty acid	(Astuti et al., 2018) (Chakravorty et al., 2016) (Pereira et al., 2003)

Furthermore, mealworms exhibit a diminished ecological footprint concerning greenhouse gas discharges compared to orthodox animal husbandry frameworks (Oonincx & De Boer, 2012).

Correspondingly, in Thailand, the poultry industry is linked to a substantial 89% escalation in greenhouse gas discharges when evaluated in terms of consumable protein, in contrast to crickets (Halloran et al., 2017). In most disclosed parameters, cricket cultivation demonstrated a commensurate or diminished influence compared to poultry production. In contrast to the environmental repercussions of various meat alternatives, as assessed through a comprehensive array of criteria, it was determined that commodities derived from insects and soy meal registered the most modest ecological footprint (Smetana et al., 2016).

Assessing the ecological ramifications of utilizing housefly larvae as fodder concerning established standards presents a more intricate challenge. While fish meal is correlated with elevated energy consumption and the attendant upsurge in greenhouse gas discharges, the accompanying land utilization remains minimal. Conversely, the manufacturing process of soybean meal demands substantial land allocation, yet its energy consumption is relatively parsimonious. When making a direct juxtaposition between housefly-derived sustenance and a blend comprising equal parts of fish and soybean meal in a 50:50 ratio, the following discernible reductions are observed: a precipitous drop of 98% in land requisition, a noteworthy 61% decrease in the overall warming potential with global ramifications, and a substantial reduction of 38% in energy utilization percentage (van Zanten et al., 2015). The net energy prerequisite for housefly-based sustenance is around 40% greater, and the associated greenhouse gas emissions are roughly double in magnitude, in contrast to the earlier mentioned 50:50 amalgam. Nevertheless, land usage is still drastically curtailed, registering a substantial 97% reduction. As reiterated previously, the nutritional feed employed within a production framework plays a crucial role in dictating the environmental implications intrinsic to the system.

Regulatory and Policy Consideration

Laws and guidelines about insect consumption that is fit for consumption must hold utmost significance in the governance of both burgeoning and advanced nations. This is imperative to guarantee a supply chain of this comestible, minimizing or eliminating potential hazards, extending from the agricultural source to the ultimate consumer. The dietary habits of numerous individuals have undergone substantial transformations of late, driven by an escalating awareness of their entitlement to high-grade and secure sustenance. This shift unquestionably extends to edible insects and their byproducts, particularly resonating with Western consumers known for their cautious approach toward embracing entomophagy. In many developing nations where entomophagy is ingrained in tradition, the absence of regulatory frameworks about the processing, producing, and selling of consumable insects results in a dearth of impediments to their utilization (Dobermann et al., 2017).

Conversely, the scenario varies in Western nations, where a substantial portion of them actively formulate, scrutinize, or execute regulations pertinent to the matter at hand. As an illustration, EFSA (European Food Safety Authority) recently mandated that any insect-derived edibles intended for individual's intake be categorized as innovative foods. Novel foods primarily encompass those devoid of a historical record of human consumption in the relevant country. European Commission (EC) delineates innovative food as "Nutrition that had not been ingested to a substantial extent by individuals in the European Union (EU) prior to May 15, 1997, marking the initiation of the initial regulation on novel food. Regulation European Union (EU) No 2015/2283, occasionally denoted as the updated Novel Food Regulation, primarily aims to uphold consumer well-being by guaranteeing the safety of edibles. It furnishes directives that must be strictly followed for any novel foods destined for commercial distribution within the European Union (EU) market. This regulation provides European Union (EU) consumers with an extensive array of secure, distinctive, and groundbreaking dietary options, encompassing selections originating from nations in the developing world. As per OJEU (Official Journal of the European Union), the endorsement of novel foods is contingent upon adherence to specified regulations, encompassing safety for consumption, transparent labeling to prevent consumer deception, and non-deviation in a manner that could nutritionally disadvantage the consumer if employed as substitutes for other food items. A diverse array of edibles is presently categorized as novel foods following Regulation (EU) No 2015/2283, and they are incorporated into the authorized Novel Foods roster of the Union. Novel foods encompass edible insects, whole insects or fragments, and components derived from them, like meals/flours. Additionally, substances not originating from entire edible insects or their components, such as insect extracts, fall under this classification (Imathiu, 2023).

In the Occidental realm, entomophagy encounters limited acceptance, notwithstanding that specific European nations like the Netherlands, Belgium, the United Kingdom, and France permit the utilization of various insect species as sustenance. Furthermore, they have instituted legislative structures to facilitate such allowances (Lähteenmäki-Uutela & Grmelová, 2016). Nonetheless, the erstwhile permissive stance in Belgium was rescinded, supplanted by the enforcement of interim measures. The subsequent insects align with the prerequisites of the transitional phase: house cricket, African migratory grasshopper, banded cricket, lesser mealworm, and yellow mealworm.

CONCLUSION

Insects, as both food and feed, play a significant role in ensuring food security and enhancing the people's livelihoods. Insects are crucial as nutrient sources for humans and a diverse range of other animal species. Edible insects are widely acknowledged for their considerable economic, nutritional, and flavor-related merits. Insects such as house crickets, fruit flies, house flies, black solider fly, and mealworms serve as valuable suppliers of essential micronutrients. Edible insects are abundant in protein and amino acids, particularly essential amino acids crucial for the human body. They also hold significant medical, commercial, and ecological importance. Therefore, these edible insects should be considered in a world where human nutrition poses a significant challenge.

FUTURE DIRECTION

Consumable arthropods seem to proffer a substitute and enduring method for satisfying the dietary requirements of a progressively burgeoning global populace (Mlček et al., 2014; Sun-Waterhouse et al., 2016). Nonetheless, numerous hurdles exist that necessitate resolution when harnessing the latent capacity of comestible arthropods to bolster food security. An in-depth inquiry into the nutritive worth and physiological advantages of various insect taxa must be undertaken with meticulous scrutiny, forming the groundwork for their endorsement as a salubrious alimentary resource. An exhaustive assessment of the ecological ramifications and long-term viability of the cultivation, acquisition, and manufacture of arthropods is requisite, enabling comprehensive contrasts with conventional agriculture and livestock husbandry, which are perceived to engender more substantial ecological harm. The potential socio-economic advantages linked to the collection and cultivation of insects to enhance nourishment security within economically disadvantaged environments necessitates additional elucidation. Arthropods appear to entail minimal concerns regarding animal well-being, although the extent of their susceptibility to distress and suffering remains unclear (Van Huis, 2021).

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AUTHORS CONTRIBUTIONS

Alishbah Mohsin, Ayesha Younas, and Aleena Kanwal drafted the manuscript. Yasir Niaz, Shabbir Hussain, Muhammad Ahmad Mudassir, Kamran Ikram, Muhammad Saqlain Zaheer, and Muhammad Ali provided the guidelines for writing and revising the manuscript. All authors read and approved the final manuscript.

CONSENT TO PUBLISH

The manuscript entitled, "Insect as a Promising Food Source: Implications for Sustainable Consumption across Species. A Review" is prepared in accordance with the Guide for Authors available on the journal's website and it has not been published elsewhere in part or in its entirety. All authors attest to the validity of its contents and agree to submission.

CONFLICT OF INTEREST

The authors declare no competing interests.

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