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Review

Beyond Proteins—Edible Insects as a Source of Dietary Fiber

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Abstract: The consumption of insects as an alternative protein source is acceptable as a sustainable alternative to mainstream protein sources. Apart from containing a high protein content, insects also have dietary fiber in the form of chitin, which helps to enrich gut microbiota. The importance of the gut microbiome in general health has recently been underlined for humans, farm animals, pets, poultry, and fish. The advances in 16S RNA techniques have enabled the examination of complex microbial communities in the gastrointestinal tract, shedding more light on the role of diet in disease and immunity. The gut microbiome generates signals influencing the normal nutritional status, immune functions, metabolism, disease, and well-being. The gut microbiome depends on dietary fiber; hence, their diversity is modulated by diet, a relevant factor in defining the composition of gut microbiota. Small shifts in diet have demonstrated an enormous shift in gut microbiota. Edible insects are an excellent source of protein, fat, and chitin that could influence the gut microbiota as a prebiotic. Chitin from insects, when consumed, contributes to a healthy gut microbiome by increasing diversity in fecal microbiota. Moreover, a high fiber intake has been associated with a reduced risk of breast cancer, diverticular disease, coronary heart disease, and metabolic syndrome. This review presents edible insects with a focus on fiber found in the insect as a beneficial food component.

Keywords: chitin; chitosan; gut health; microbiota; probiotics

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1. Introduction

More than 2 billion people around the world are already consuming insects, directly or indirectly, making them an important part of diets. Most insects contain the essential nutrients required by humans and animals, which include fats, proteins, fiber, vitamins, and, in addition, minerals [1]. The nutrient composition of many edible insects is comparable to that of other traditionally consumed animal protein sources. Therefore, they may act as an alternative source to other mainstream animal protein sources such as chicken, beef, and fish. Relative to livestock, insects are a more sustainable and efficient food source, requiring minimum water and space [2]. The consumption of insects for food is a traditional practice in many societies, especially in Asia, Latin America, and Africa, and is common in low-income groups in these countries, often collected from the wild. By contrast, in most Western countries, people view entomophagy with disgust or even as culturally inappropriate; therefore, consumption is infrequent [3]. However, with greater awareness of the environmental footprint associated with the livestock industry and concerns around the sustainability of agriculture and the impacts of climate change on productive systems, there is an opportunity for using insects as an additional and healthy protein source. Currently, the use of insects as protein sources within the European Union has a legal basis [4], which has allowed many startup companies to engage in insect farming for pigs, poultry, and fish. Already, yellow mealworm is extensively farmed, and other insects such as crickets and grasshoppers may be farmed for human consumption. There is a possibility of increased consumption of insects, especially due to their potential to provide other uses beyond their nutritional benefits. The isolation of specific compounds that can be used as food supplements, the dietary fiber contained in insects, and their use as high-protein supplements in sports will likely increase the usage of edible insects [5,6].

2. Edible Insects

Most countries are currently embracing insect farming for pet food, poultry, pigs, and fish. The inclusion of edible insects in food production has the potential to benefit the environment and animal and human health by supplementing other animal-sourced proteins. This would help save resources such as land and water; reduce greenhouse gas emissions, and eventually address issues of food security [7]. Concerning nutrient composition, edible insects have a sufficient number of essential amino acids, fatty acids, fiber, vitamins, and minerals [8]. This is a suitable alternative to livestock, fish, and poultry and can replace fishmeal in animal feed as a more suitable and efficient protein source, often reared on organic waste [9].

The increased interest in agricultural resources and the decreasing ecological impact of food production have shown the consumption of insects rising at a global rate, and their farming for feed may offer a sustainable means of food production [10]. To satisfy the demand for sufficient insect quantities, farming insects is gaining fast momentum across the globe. Edible insects not only provide common nutrients but also bioactive substances such as chitin and antimicrobial peptides [6]. The nutritional profile of insects can be highly variable and depends on the insect species, the feed used, and the developmental stage [11]. Environmental factors can also affect their nutritional value, and this may include the day length, light intensity, temperature, and humidity [11]. Insects' protein content varies between 12 and 70% (Table 1), they may be highly digestible, and their consumption may contribute to the total protein intake, enhancing nutritional quality in the human diet. Edible insects meet the daily energy and nutrient requirements, from their fat, amino acid, and mineral composition. The high amino acid content in insects and the presence of omega fatty acids allow them to act as dietary supplements that help alleviate disease [12]. Therefore, using edible insects may confer positive health implications.

The total fat content of insects ranges between 6 and 43% (Table 1) and is generally similar to that of animal fats and vegetable oil [12]. However, in comparison with beef and pork, insects are particularly rich in mono and polyunsaturated fatty acids. The high content of unsaturated fatty acids may be problematic due to oxidation during the handling and processing of insect products, and this may lead to a food safety risk. Processed food with high protein and fat contents is prone to spoilage due to oxidation [13]; hence, food products processed with whole insects as ingredients may fall into this category. If this is the case, defatting may be a solution to the high fat content and the obtained fat, used on its own or in combination with other products. Some insects contain phenols and flavonoids, which have antioxidative properties. Substantial levels of these compounds are seen in silkworm larvae, crickets, and grasshoppers [14].

Table 1. Nutrient content in edible insects approved within the EU according to the selected literature.

Insect Type	Protein (%)	Fat (%)	Chitin (%)	References
Mealworms	16–45	20–43	1–3	[15–18]
Crickets	15–47	7–29	1–12	[16,19,20]
Grasshopper	50–70	6–11	5–15	[16,21]
Black soldier fly	12–55	11–29	3–15	[17,18,22]

Although edible insects appear to be a valuable source of nutrients and bioactive compounds, some compounds are seen as antinutritive, such as chitin. Chitin is a source of dietary fiber obtained from the exoskeleton consisting of a long-chain polymer of N-acetyl-glucosamine. Chitin can be digested by humans, into a deacetylated form, chitosan, which is regarded as a functional food component [23] providing beneficial effects as an antimicrobial and an immune modulator in cholesterol reduction, wounds, and chronic disease healing [23]. Studies have shown that chitin has the potential to improve gastrointestinal health when gut microbiota ferment it [24]. It can also increase immune function by immune modulation, decreasing the risk of bacterial infection through antimicrobial effects, and reducing chronic inflammation that may be associated with cancer and cardiovascular disease [23,25]. Insect chitin, therefore, has great potential to improve human and animal gut health by regulating the gut microbiota as a dietary fiber.

2.1. Limitation of the Possible Widespread Use of Insects

Disgust and neophobia are limiting global acceptance of insects and their products [3]. Every new product faces some amount of resistance, and there is hope that, if the advantages of using edible insects will outweigh the disadvantages, then adoption will be achieved at some point. The addition of edible insects to products will greatly help reduce disgust since the consumer will reap the benefits of edible insects without having to see the insects themselves. The extensive use of edible insects is under development and is not yet widespread, especially in the colder geographic regions where insects are limited. Insects are very sensitive to temperature and humidity changes, and their rearing should ensure a well-maintained environment. Rearing insects in these regions will require specialized units that will enable climate control in unfavorable seasons. Often, these new technologies are expensive, limiting the widespread production of edible insects and leading to reduced use due to inaccessibility [26]. Currently, edible insects are therefore not available in many outlets, which is a limitation for new users who would desire to explore.

Inaccessibility does not only affect colder regions and the tropics, where insects are traditionally used, but its use is also limited to seasonality, and with the recent climate change occurrences, the swarming of edible insects cannot be predicted and hence cannot be included as a stable food [27]. This can be improved by the widespread farming of insects, although in the regions where people are collecting insects from the wild, there is a lack of knowledge and tools to be used for insect rearing [28]. When reared, insects have a short life span, which may hinder their use as long-term application tools. The tools and equipment used for raising insects have been fabricated for other uses and are therefore not food-grade material. The exact food safety risk posed by the use of this equipment has not been fully accessed, and this is yet another limitation. There is a need for complex and specialized training for personnel to handle insect rearing. The training can be expensive and time-consuming, requiring specialized knowledge and skills. Pioneer farmers have reported frequent colony collapse, which may be caused by an extensive lack of knowledge [29].

Another major setback involving the widespread use of edible insects is the limited number of edible insects that have been approved for human food. So far, grasshoppers/locusts, crickets, and yellow mealworms have been approved for production and use within the European Union [4]. The other limitation may be caused by the possible allergic reaction to insect products [30], through contact, consumption, or inhalation. Insects can cause allergic reactions that include itching skin, dizziness, and shock [31]. People who would like to explore edible insects should ensure that the insects are sourced from known, reputable sources and are well cooked to reduce the risks associated with foodborne illnesses [32]. When considering consuming insects, an individual with a history of allergy reactions from crustaceans or another protein source should be aware of possible allergic reactions from edible insects [33].

Like other protein sources, insects can carry harmful bacteria, viruses, toxins, and parasites [34]. These can cause foodborne illnesses, especially if the insects are not well-cooked. Depending on the rearing practices, insects can absorb and retain chemicals from the environment that may include heavy metals, pesticides, and other process contaminants [35]. The initial analysis carried out has shown that insects do not concentrate on these harmful substances [36], although there is a need for a complete risk assessment.

2.2. Possible Limitations of Insect Use within the European Union

Insect farming will require more insects to be killed to provide the required tones of insect proteins [35]. Currently, the large-scale production of insects is under development, and there is a knowledge gap on the humane extermination of insects during harvest; this in itself is a setback since the EU laws on the protection of animals kept for farm purposes do not include invertebrates and, in this case, edible insects [37]. There is a need for the inclusion of insects in the legal regulations, which is key to the expansion of insect farming and effective marketing [35].

Large-scale insect farming will likely promote the factory farming of insects instead of promoting more sustainable food systems, and the energy requirement for controlled insect breeding has not been quantified; therefore, its impact is still unknown. There is also a need for more research on insect welfare and the impact of large-scale production on the ecosystem. Edible insects have the opportunity to contribute to the circular economy [38] when insects are fed organic waste, although when they are fed low-quality food waste and straws, the live weight and nutrient quality are low, with high mortality rates [39]. Food safety is the cornerstone of the modern food industry and therefore important for EU legislation, and edible insects are no exception [35]. Currently, manure, catering wastes, and other wastes are not allowed as insect feed in the EU, and therefore, insects are likely to be fed commonly available animal feed and may end up not contributing much to the circular economy [35]. In third-world countries, black soldier flies have been fed organic waste [40,41] and sometimes sewage sludge [42,43]. Unfortunately, edible insects within these production systems cannot be traded in the EU, and therefore, there is a need for harmonized practices for better global trade in the edible insect industry. There may be an opportunity for edible insects to contribute to the circular economy in the EU if waste is redefined. Often, fruits and vegetables from outlets expire due to their perishable nature and are discarded. The need to look at the enormous quantities of vegetable leftovers in agriculture, in supermarkets, and in households as possible insect feed may better contribute to the circular economy.

3. Chitin and Chitosan as a Dietary Fiber

Dietary fibers are carbohydrates not digested in the body and can travel through the digestive system, helping the system to stay healthy [44]. The soluble dietary fiber can dissolve sugar and cholesterol, while the insoluble ones help in bulking and therefore facilitate better bowel movement [44]. Chitin is an abundant natural polymer with a structure almost similar to that of cellulose, while chitosan is the deacetylated form of chitin and is soluble in slightly acidic conditions [45]. Chitin is the main component of crustacean shells, insects' exoskeletons, and the cell wall of fungi. The major source of chitin in the world is crustaceans' shells, which usually accumulate as large waste and are a major concern of this industry [46]. The chitin content from crustaceans is enormous but is extracted before use, often using aggressive chemicals, while chitin from insects and some fungi is converted directly to chitosan (Figure 1).

Crustacean and insects chitin are cross-linked with proteins, while fungal chitin is associated with other polysaccharides such as glucans that are often in higher quantities than the chitin [47]. During extraction, the mycelial or fruiting bodies are used for fungal chitin extraction, the shells for crustaceans, and the pupae or whole insects for the extraction of chitin from edible insects [47]. Marine sources have the greatest potential for chitin yield, but sources are seasonal and limited due to climate change; moreover, the shells are also often exposed to infections and contaminations, which may affect the quality of chitin obtained [48]. Fungi is the second-largest source of chitin that has a commercial advantage as a vegan source of chitin and chitosan (Table 2). Some fungal species can be a source of chitosan directly without having to undergo deacetylation [49]. The widely studied species for direct chitosan production are Zygomycetes, Ascomycetes, and Basidiomycetes, although this has not been conducted on an industrial scale [49]. Insects are usually promoted due to their high protein and fat contents, and the addition of fiber is likely to increase the benefits of this novel food. Figure 1 outlines the major source of chitin; edible insect chitin can be consumed and deacetylated by the host enzymes. Edible insects contain varied amounts of chitin depending on the developmental stage [50]. The older the insect, the higher the chitin content. This has partly contributed to the increased interest in chitin and chitosan from farmed edible insects. More chitin and chitosan from exuviate can be obtained after the emergence of the adult from the pupae shell. This can provide additional chitin extraction material from the rearing of the black soldier fly, and this contributes to a circular economy [30].

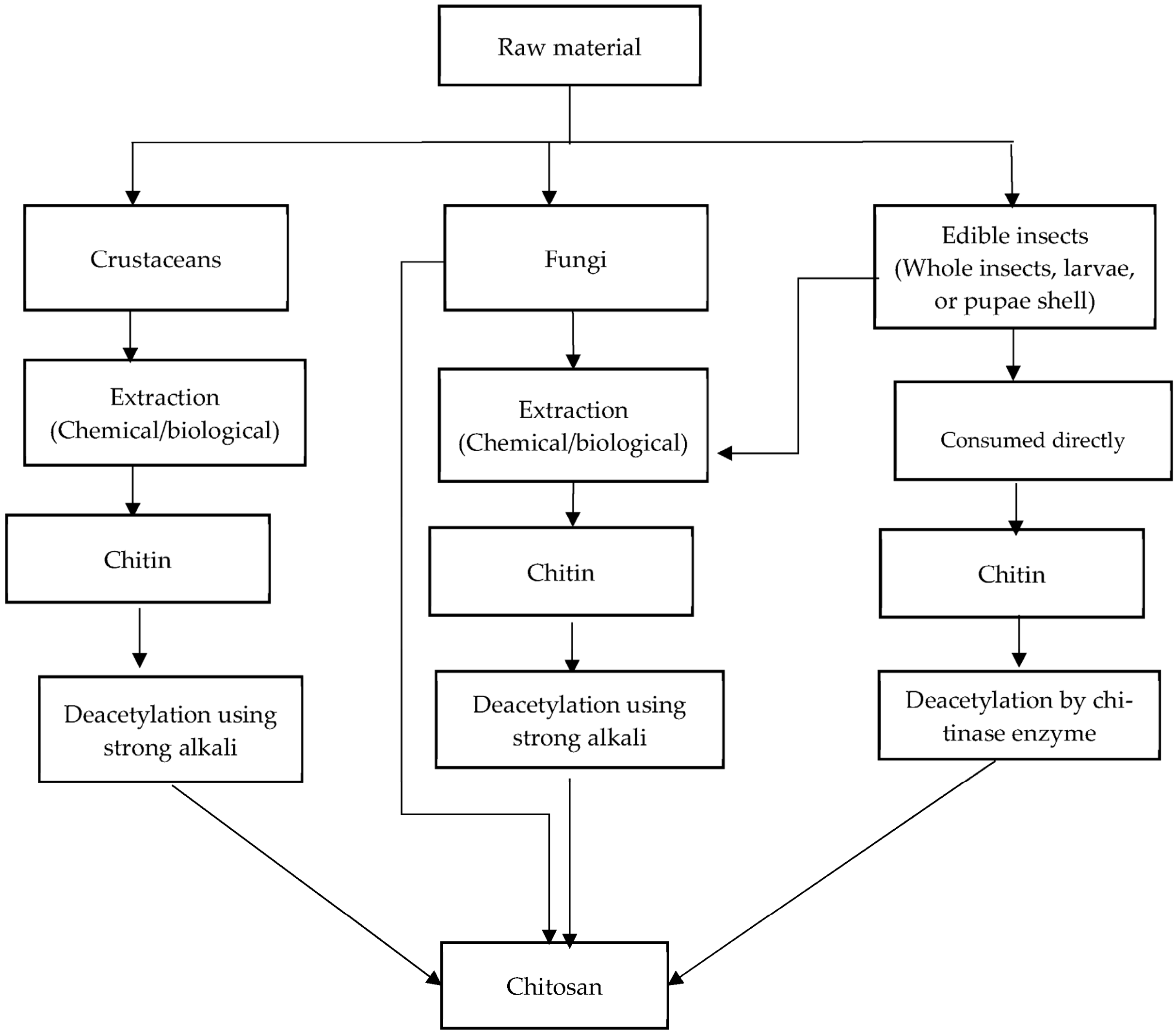

Figure 1. Process of obtaining chitosan from various sources.

Insects, when consumed whole, contain chitin that will act as dietary fiber both in humans and in animals. Industries in the domain of beneficial insect breeding are witnessing rapid growth, and the market estimation of edible insects for food and feed is estimated to increase, with the current estimation being that more than EUR 1 billion has been invested in the insect sector [51]. The importance of chitin and chitosan as food relates to their outcome as a dietary fiber and hence a functional ingredient, since chitosan is a novel food ingredient [52]. Chitosan is used as a food quality enhancer, and products containing chitosan are sold in Japan for their cholesterol-lowering ability [53]. Apart from its use in humans, chitin and chitosan have also been used in soil to improve plant health [54], to help improve growth in chicken [55], to improve immunity in fish [56], and to relieve pathogenic bacteria-induced retardant growth in pigs [57]. Table 2 highlights the three main sources of chitin and chitosan, depicting the advantages and disadvantages of each source according to the cited literature.

Table 2. Major chitin and chitosan sources.

Source	Advantages	Disadvantages	Reference
Crustaceans Content 16–49%	The highest content of chitin; hence, it is viable for industrial extraction	Limited to seasonal and regional variations High mineral content requiring aggressive extraction Highly susceptible to heavy metal contaminants	[47,48]
Fungi Content 1–29%	Possibility of the direct production of chitosan by some species No seasonal variations Can be produced by solid phase fermentation that can control for desired chitin/chitosan production Important as a vegan source of chitin and chitosan Consistent physiological and chemical properties	Limited availability and low content Industrial production not widely established	[47,49,57–59]
Edible insects Content 6–36%	Can be consumed directly Can be produced all year round Can be produced by bacterial fermentation With industrial insect farming, chitin can be available as a cheap byproduct	Commercial production has not been established The risk of allergic reactions has not been fully described	[47,58,60,61]

Chitin is a viscous dietary fiber that binds cholesterol, hence decreasing its absorption and leading to the excretion of excess cholesterol [45]. Chitin is non-digestible in the upper gastrointestinal tract, with high viscosity and high water binding capacity, while at the lower part of the gastrointestinal tract, it has low water holding capacity that helps in the effective reduction of cholesterol by the dietary fiber. The lower part of the gastrointestinal tract contains microorganisms that secrete chitinase, which can digest chitin, releasing bile acids and sterols that are excreted without absorption [45]. The production of short-chain fatty acid after the consumption of chitin has not been demonstrated in humans but has been demonstrated in poultry [62]. This study reported that a diet consisting of black soldier fly larvae affected the production of large intestinal microbiota and short-chain fatty acids in poultry [62]. This may have been due to the prebiotic potential of chitin that promotes the gut health and, subsequently, the overall health of the poultry. Additionally, the increase in butyric acid and short-chain fatty acids optimizes intestinal health and inhibits pathogenic bacteria [63].

The human gastrointestinal tract is home to a host of bacterial cells that are slightly higher in number than human cells [64]. The ideal number of bacteria in the gut has not been determined due to the huge diversity caused by genetic variability, the difference in diet, and health [65]. Research has demonstrated that microbiota in the human gut respond to nutritional changes [66–68]. When this happens, the microbiota generates signals that influence the normal nutritional status, metabolism, immune function, and disease progression, which greatly contribute to overall well-being [69–71]. In addition, there is a general agreement that healthy microbiota are associated with better health [72,73]. People suffering from obesity have a lower diversity of gut microbiota commonly known as dysbiosis [74]. Low microbial diversity is associated with chronic non-communicable diseases [75,76]. The diet is the most relevant factor in defining the composition of gut microbiota [77]; indigestible fiber is the primary energy source and can be fermented by the microbiota and hence acts as a prebiotic. A healthy diet leads to a more diverse and healthy microbiome [78,79]. The ability to maintain healthy microbiota is useful in activating the host's immune system and other mechanisms that may constitute a new therapeutic strategy for preventing chronic disease.

Dysbiosis is a microbial imbalance in the body, leading to impaired microbiota, which is a commonly reported condition in the gastrointestinal tract, caused by small intestinal bacterial or fungal overgrowth. Normal microbial colonies are beneficial and help aid the digestion and synthesis of vitamins such as B3, B5, B6, B7, B9, B12, and vitamin K [80], which are involved in myriad aspects of the microbial and host metabolism. When there is a microbial imbalance, the microbes exhibit a decreased ability to check each other's growth; this can cause the overgrowth of one of the disturbed microbes, which may damage beneficial ones in a vicious cycle [81]. Usually, microbial colonies excrete different types of waste that the body effectively manages, but oversized microbes excreta can cause negative outcomes. These may include pathogenic members taking hold of the gut environment [81]. Imbalances in the gut microbiota are associated with metabolic and non-communicable diseases, gastrointestinal conditions, allergies, asthma, and environmental enteric dysfunction (EED) [74]. Relationships between the diet, nutritional status, immune system, and microbial ecology are important as we look for new ways to feed healthy foods to a human population predicted to expand to 10 billion by 2050.

Gut health is determined by gut microbiota commonly called probiotics. Probiotics are living organisms that benefit the host when available in adequate amounts, though even dead bacteria and their products confer probiotics benefits [82]. Prebiotics are substances that can maintain normal gut microbiota when there is an imbalance; therefore, probiotics and prebiotics are dependent on each other. The most popular probiotics are the lactic acid bacteria that help in the fermentation of non-digestible polysaccharides [82].

Insect Chitin as a Prebiotic

The nutritional value of edible insects is well documented, as described above, but other potential benefits beyond protein and fat have not been widely documented. Studies have reported important biofunctional effects of various components of edible insects such as chitin, fat, and protein [83–85]. The biofunctional properties highlighted include antioxidant properties, anti-inflammatory microbial modulation, and cholesterol reduction ability [83]. The fermentation of prebiotics produces breakdown products such as short-chain fatty acids that enter the bloodstream and thus help other organs far from the digestive system [84]. A positive change in the composition and metabolic activity of the host gut is of great interest due to the important role of intestinal microflora in human health. Prebiotics can have positive effects on host organisms by selectively stimulating beneficial gut bacteria [85].

Chitin is fermented in the colon to form short-chain fatty acid that has a mild laxative [86] effect, although this has not been carried out in human studies. The beneficial effects of chitin and chitosan in fish poultry and pigs have been successfully tested, and clinical studies ascertaining these benefits in humans are limited, with some studies mimicking this effect in vitro [55–57]. The following table lists in vitro and in vivo studies of insect chitin concerning human health (Table 3).

Table 3. Edible insects in gut health and disease.

Study	Methods	Main Findings	Recommendations	References
Critical review on the effects of chitin and derived polysaccharides on human gut microbiota	Review	Whole insect meal is beneficial in the modulation of gut microbiota. Chitin-derived chitosan has the potential to be prebiotic when ingested with low protein diets, as a high protein content may counteract the benefits of chitin. Chitosan promotes the growth of beneficial bacteria, suppresses potentially pathogenic bacteria, has anti-inflammatory and immune stimulating properties, and may also help to treat obesity and diabetes	There is a need for more research to promote the use of chitin and chitosan as human food.	[65]

Table 3. *Cont.*

Study	Methods	Main Findings	Recommendations	References
Effects of consuming whole cricket powder on gut microbiota; $n = 20$	Stool analysis	Enhanced growth of *Bifidobacterium animalis* and reduced TNF-α	Need to understand underlying mechanisms	[87]
The potential of the edible insect as a prebiotic	In vitro bacterial composition of human fecal microbiome	Changes in microbial composition induced by undigested insect material in the batch culture—particularly, an increase in *Faecalibacterium* spp., previously associated with anti-inflammation	There is a need to test this in vivo	[88]
In vitro gastrointestinal digestion of cricket protein hydrolysates	Sequential fractionation	Protein peptides from edible crickets have positive effects on inflammation and hypersensitivity	Further research on the underlying mechanisms of the anti-inflammation effects of cricket peptides	[89]
Adding insects to the diet	Review	Reduced nutrient deficiencies and beneficial effects of insect bioactive compounds in diseases such as coronary heart disease, inflammation, and cancer	Bioactive compounds derived from insects should be used to formulate diets for better health	[90]
Benefits of eating insects and shrimps	Review	Insect extracts have antioxidant properties and the potential to be used in low-sodium diets	There is a need for further in vivo and clinical studies	[91]
Environmental and health benefits of edible insects	Review	Improved gastrointestinal health, reduced infection, and improved immunity. This could be due to reduced inflammation and a high protein content that is important in building muscles	Need for well-designed clinical studies	[92]
Consumption of insect-derived protein	Double-blind controlled trial	Increased muscle synthesis at rest and during exercise	Increase the use of insects to provide high-quality proteins	[93]
The antioxidant ability of insect products	Review	Edible insect-derived products can help the oxidative stress-mediated infection	Research to develop oxidative molecules from edible insects	[94]
Edible insects in complementary food	Randomized control trial	Improved micronutrient status in infants	More research on nutrient bioavailability; there is also a need to use edible insect products to save humanitarian situations, especially in malnourished children	[95]
Effects of edible insects on gut health	Review	Improved gut health and microbial diversity, and increased secretion of short-chain fatty acids	Study of digestion and bioavailability of chitin in humans	[86]
Prebiotic potential of insect chitosan	In vitro study	Inhibition of pathogenic bacteria	Need for in vivo studies to test its use as a prebiotic.	[96]
Feeding bugs to bugs	Batch culture inoculation	Modulation of gut microbiota	Need for in vivo studies to gain insight into the required dosage	[88]

There are other important types of prebiotics, the majority of which are subsets of carbohydrates [84]. Among the most important prebiotics are fructans, which consist of inulin and fructooligosaccharides, which stimulate bacteria species capable of fermenting them [84]; lactic acid bacteria are stimulated the most, although other bacteria species may also be promoted. Galacto-oligosaccharides are also prebiotic and can strongly stimulate Bifidobacteria and lactobacilli [97]. Starch that is resistant to digestion in the upper part of the digestive system can produce butyrate during fermentation and can promote the growth of Firmicutes [98]. Pectin and cocoa-derived flavanols stimulate lactic acid bacteria [84]. The use of edible insects as prebiotics would be beneficial when compared to other sources due to their occurrence together with high protein, fat, and fiber contents. Most animal protein sources are considered of high quality but lack dietary fiber; on the contrary, edible insects can provide a high animal protein source with fiber that could act as a prebiotic. A good prebiotic would work in the local gastrointestinal tract to support the selective growth of beneficial bacteria [96]. The gut is constantly exposed to substances and toxins that are likely to cause dysbiosis [74]; therefore, frequent interventions to ensure balanced microbiota in the gut are necessary.

4. Conclusions and Outlook

The gut microbiome plays an important role in disease, and taking prebiotics helps restore normal gut flora by promoting the growth of beneficial bacteria and reducing the risk of chronic infections. Chitin from edible insects may be a functional prebiotic due to its ability to stimulate the growth of certain beneficial bacteria, which may help solve gut health problems by acting directly as an antimicrobial or as a prebiotic to feed probiotic bacteria. Although prebiotics have tremendous benefits, there is the limitation of individual variability caused by the diversity of microbiota present due to diet, race, age, and health status. The effect is likely dose-dependent, and despite the consumption of edible insects by traditional or new consumers, it is necessary to determine the effective amount that will influence gut health. The ingestion of insects during swarming season has been associated with diarrhea and bloating in the past, which may be due to intolerance of chitin in some people. Therefore, consumers should be in consultation with health professionals to avoid unforeseen negative effects. The production of prebiotics from edible insects may require additional steps to ensure a high quality and meet desired properties, and this can be expensive.

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