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Edible crickets as a possible way to curb protein-energy malnutrition: Nutritional status, food applications, and safety concerns

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ABSTRACT

Protein malnutrition is a major public health concern in the developing world. The livestock products are a good source of high-quality protein, but the livestock industry is a source of pollution and one of the leading causes of climate change because the slaughtering of animals results in the accumulation of waste, offals, and several inedible body portions. The rapid increase in the human population and inadequate supply of traditional protein sources have driven a search for novel and alternative protein sources such as edible insects. This review extensively explores the nutritional value, allergenicity, and safety considerations associated with consuming common house crickets and other related insect species. A wide range of cricket protein-based products are currently available and provide some attractive options to the consumers such as protein-enriched bakery products and gluten-free bread for celiac patients. The cricket protein hydrolysates are used as preservatives to improve the stability of cheddar cheese and goat meat emulsions during storage. The risks associated with edible crickets and their products are bacteria, mycotoxins, polychlorinated dibenzodioxins, pesticide residues, heavy metals, and the presence of allergenic proteins.

1. Introduction

Malnutrition, unsustainable energy, and contaminated water are some of the major challenges faced by the world in the present days (Awual et al., 2023; Awual et al., 2024; Kubra et al., 2021; Rasee et al., 2023; Salman et al., 2023). The demand for protein-rich foods is likely to increase with the increasing human population which is expected to reach 9.1 billion by 2050 and will make it difficult to supply protein in a sustainable way (Henry et al., 2018). Supply of dietary proteins in such a big quantity without affecting the environment and with a low carbon footprint will be extremely challenging and will require additional measures such as a shift in the diet towards other non-traditional and alternative protein sources (Ahmad, Rizwan, & Saeed, 2022; Khan, Nawaz, Saeed, & Khan, 2022; Mubashir, Ghani, & Mubashar, 2022; Mehnaz et al., 2023; Anjum et al., 2023; Fonkem et al., 2022; Bastamy, Raheel, Ellakany, & Orabi, 2022; Raza et al., 2022). Animal and chicken-based meat products may have microbial hazards like bacteria (*Campylobacter*, *Escherichia coli*, *Staphylococcus,* and *Salmonella*), protozoa (*Sarcocystis* and *Toxoplasma*), viruses (Norovirus, Hepatitis A virus, and Hepatitis E virus) associated with them (Utari, Warly, & Hermon, 2023; Husmaini, 2023; Aini et al., 2023; Mahmood et al., 2022; Zia, Shah, & Habib, 2022; Elsayed et al., 2022; Rehan, Qureshi, Kausar, & Saleemi, 2023; Dik et al., 2023; Degla et al., 2022; Raza, Hussain, & Khan, 2023). Entomophagy (the practice of consuming insects as a source of nutrition by humans) or eating insects as food is an old-age practice that is believed to provide essential nutrients to more than two billion people worldwide (Barsics et al., 2017). The people in Asia, Central America, Africa, and South America have a long history of eating

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insects as food. Bees, ants, beetles as well as crickets, and grasshoppers are some of the insects that are commonly relished in some cultures (Lange & Nakamura, 2021).

Edible crickets are high in protein content (50–60%) with a biological value of 93.02%, net protein utilization of 75.20%, net protein ratio of 3.04%, protein efficiency ratio of 1.78%, and true digestibility of 80.82% (Oibiokpa, Akanya, Jigam, Saidu, & Egwim, 2018). The incorporation of insect powders or flours to make different food products are more liked by the people as compared to eating insects as a whole (Hartmann, Shi, Giusto, & Siegrist, 2015; Tan et al., 2015). For instance, bread enriched with crickets showed an impressive nutritional profile and better sensory acceptance (Osimani et al., 2018). da Rosa Machado & Thys, (2019) supported the possibility of using flour of crickets as an alternative source of protein for making gluten-free bread (da Rosa Machado & Thys, 2019). Insect protein powders have enabled the incorporation of insects into food products. Whey protein is one of the most popular protein source for protein drinks, however, consumers have also been looking for alternative and cheaper sources of protein other than whey (Parker, Lopetcharat, & Drake, 2018).

This review aims to reveal the potential of crickets as a dietary ingredient to treat widespread protein-energy malnutrition through the development of various nutritious and well-known food products. A wide range of food products including milk, meat, cereal, and bakery products have been developed using protein-rich cricket powder (CP) or cricket flour (CF) as an ingredient. The review will expand our understanding of using crickets as a dietary ingredient for developing different food products. It will generate insights necessary to develop other food products using other insect proteins. Previous reviews on the same topic explored the possibility of utilizing common house crickets to develop different novel and nutritious food products but this review describes the nutritional status of all edible species of crickets including common house cricket (*Acheta domesticus*), two-spotted cricket (*Gryllus bimaculatus*), Jamaican field cricket (*Gryllus assimilis*), tropical house cricket (*Gryllodes sigillatus*), and armored cricket (*Acanthoplus discoidalis*), their potential to produce protein-enriched and value-added food products, their preservation applications along with their safety and allergenicity concerns. It covers almost every aspect of using edible crickets as a food ingredient to give new future research directions.

2. Nutritional status of edible crickets

For various ecological and environmental advantages including sustainability, animal welfare, nutritional value, and global food security, the use of insects as a source of protein is increasing rapidly and has recently attracted the attention of food processors and researchers. Udomsil, Imsoonthornruksa, Gosalawit, and Ketudat-Cairns (2019) assessed the nutritional composition and functional properties of protein derived from the common house and two-spotted crickets which are two distinct species of edible insects. Both species showcased a substantial protein content ranging from 60 to 70% on a dry weight basis (DWB), encompassing all essential amino acids as well as a lipid content of 10–23%. It was observed that there was an abundant presence of omega-3 and omega-6 fatty acids, along with notable amounts of minerals such as sodium, calcium, and phosphorus. The findings of the study revealed that edible crickets, in their natural form or as a protein extract, have the potential to serve as ingredients in a variety of food products, offering an alternative source of nutrition. Mlček et al. (2018) determined the nutritional composition of the field crickets by using Infrared Spectroscopy, the Kjeldahl method, the Soxhlet method, and gas chromatography–mass spectrometry (GC–MS) to determine the crude protein, fat, and fatty acid composition, respectively. On a dry matter basis, the insect under investigation exhibited an average content of 55.6% for crude protein and 11.8% for fat. Among the fatty acids, palmitic (C16:0), oleic (C18:1), and linoleic (C18:2) acids were found in significant amounts. Mugova, Zvidzai, and Musundire (2022) conducted a study on the nutritional significance of the armored cricket. Their study involved analyzing the amino acids, minerals, and fatty acid profiles of the insect, as well as performing a proximate analysis. The reported energy value of the insect was 454.3 kcal/100 g. The mean values for carbohydrate, protein, fat, ash, and chitin contents were found to be 1.20%, 69.2%, 16.8%, 8.6%, and 4.2%, respectively. The insect, when weighed at 100 g, contained 11.48 mg of iron, which is sufficient to meet the daily iron requirement for an adult human (10–20 mg). Furthermore, the insect exhibited substantial amounts of phosphorus and zinc (491 mg and 4.37 mg/100 g, respectively), which meet the recommended nutrient intake for adults. The essential amino acids with the highest concentrations were leucine (60.7 mg/g protein), followed by phenylalanine and tyrosine (59.3 mg/g protein), valine (48.4 mg/g protein), lysine (46.7 mg/g protein), threonine (37.4 mg/g protein), isoleucine (26.4 mg/g protein), methionine and cysteine (20.9 mg/g protein), and histidine (16.5 mg/g). The study also reported the presence of 9 saturated fatty acids, with palmitic and stearic acids being the most abundant (2005.3 mg/100 g and 2034.5 mg/100 g, respectively) among other fatty acids. The concentrations of the palmitoleic and oleic acids were 305.2 mg/100 g and 361.4 mg/100 g, respectively as monounsaturated fatty acids (MUFAs). The concentrations of the linolenic acid and eicosapentaenoic acid (EPA) were 185.6 mg/100 g and 1598 mg/100 g, respectively as polyunsaturated fatty acids (PUFAs). In another research, Soares Araújo, dos Santos Benfica, Ferraz, and Moreira Santos (2019) studied the nutritional composition of two distinct insect species cultivated in Brazil, namely the Morio worm (*Zophobas morio*) and Jamaican field crickets. The Morio worm species exhibited a carbohydrate content of 1.39%, protein content of 46.80%, lipid content of 43.64%, and ash content of 8.17%. On the other hand, the Jamaican field cricket species demonstrated a carbohydrate content of 8.6%, protein content of 65.52%, and lipid content of 21.80%. The predominant fatty acid contents in these insects were oleic, palmitic, and linoleic acids, while iron, magnesium, and zinc were the minerals present in notable quantities.

Carolyne, John, Samuel, and Nanna (2017) evaluated the impact of harvesting time on the nutritional value of crickets to enhance the nutritional status of children in Kenya. The nutritional value of the crickets was assessed during the 4th and 13th week of their growth. For crickets older than 13 weeks, the crude protein ranged from 36 to 60 g/100 g, chitin ranged from 2.20 to 12.40 g/100 g, and total lipids ranged from 12 to 25 g/100 g. In the 9th week, magnesium concentrations ranged from 1.30 to 11.30 mg/100 g, zinc from 0.20 to 16.60 mg/100 g, and calcium from 1.40 to 19.70 mg/100 g. The findings indicated that edible crickets can be effectively utilized as food ingredients to improve child nutrition. Montowska, Kowalczewski, Rybicka, and Fornal (2019) purchased edible CPs from online shops that were prepared after raising adult common house crickets in non-European Union countries (Thailand and Canada) in different feeding and breeding conditions. It was observed that CPs under study contain protein content of 42.0 to 45.8%, fat content of 23.6 to 29.1%, fiber content of 2.9 to 6.4%, and ash content of 3.6 to 4.3%. The amounts of calcium ranged from 139 to 218 mg, iron ranged from 4.06 to 5.99 mg, zinc ranged from 12.8 to 21.8 mg, magnesium ranged from 86 to113 mg, potassium ranged from 826 to 1224 mg, sodium ranged from 263 to312 mg, copper ranged from 2.33 to 4.51 mg, and manganese ranged from 4.1 to12.5 mg in 100 g of the products. The results showed that CP can be used as an additive for the development of novel food products for celiac patients due to its high content of minerals. In another study, Brogan, Park, Matak, and Jaczynski (2021) determined the functional and nutritional characteristics of the proteins derived from the common house crickets, silkworm pupae, and locust powders using sodium dodecyl-sulfate polyacrylamide gel electrophoresis (SDS-PAGE) analysis. The proximate composition of macro-nutrients, pH-solubility of proteins, and full composition of amino acids were also determined. Locust and CPs had crude protein of >70 g/100 g of the sample whereas the powder made from silkworm pupae had a crude protein of >50 g/100 g. The 8 essential amino acids found in insect powders exceeded the recommendations of FAO/WHO/UNU for adults, but not for infants. The total amounts of essential amino

Table 1
Nutritional composition of some main edible species of crickets (average amounts present in dried powder or flour form) in comparison with livestock meat.

Nutrient category	Nutritional components	Edible crickets				Livestock meat		
		Common house cricket	Tropical house cricket	Two-spotted cricket	Jamaican field cricket	Beef	Mutton	Chicken
Macronutrients (%)	Carbohydrates	19.6–21.8	NR	0. 1	NR	NR	NR	NR
	Proteins	42.0–45.8	56.8	60. 7	56.49	20.64	21.62	22.73
	Fats/lipids	23.6–29.1	6.1	23. 4	NR	6.83	4.56	0.89
	Fiber	2.9–6.4	NR	10. 0	NR	NR	NR	NR
Micronutrients (%)	Ash	3.6–4.3	18.1	2. 8	NR	1.35	0.84	0.96
	References	(Montowska et al., 2019)	(Hall, Jones, O'Haire, & Liceaga, 2017)	(Udomsil et al., 2019)	(Bednářová, Borkovcová, & Komprda, 2014)	(Mohammed et al., 2020)	(Mohammed et al., 2020)	(Mohammed et al., 2020)
Minerals (mg/100 g dry weight)	Sodium (Na)	331–413	NR	88. 84	NR	49.55	59.75	0.5
	Magnesium (Mg)	84–125	NR	72. 94	NR	18.5	18.9	11.06
	Iron (Fe)	4.2–5.1	NR	7. 16	NR	1.8	4.05	0.41
	Calcium (Ca)	176–265	NR	105. 14	NR	6.63	10.55	7.12
	Potassium (K)	1075–1154	NR	321. 71	NR	409	345	245
	Phosphorus (P)	741–896	NR	702. 02	NR	159	152.5	128.3
	Zinc (Zn)	16–16.9	NR	14. 39	NR	3.5	4.09	3.91
	Copper (Cu)	1.8–2.9	NR	3. 86	NR	0.18	0.34	0.53
	Manganese (Mn)	2.5–2.8	NR	3. 40	NR	0.00	0.08	0.0017
	Chromium (Cu)	0.013–0.018	NR	NR	NR	0.0011	0.0021	0.00
	Cobalt (Co)	0.001–0.015	NR	NR	NR	0.009	0.00	0.00
	Cadmium (Cd)	0.004–0.006	NR	NR	NR	NR	NR	NR
	Nickle (Ni)	0.05–0.061	NR	NR	NR	NR	NR	NR
	Lead (Pb)	0.01–0.014	NR	NR	NR	NR	NR	NR
	References	(Kosečková et al., 2022)	NA	(Udomsil et al., 2019)	NA	(Mohammed et al., 2020)	(Mohammed et al., 2020)	(Mohammed et al., 2020)
Essential amino acids (g/100 g)	Histidine	0.69	0.49	1.57	1.32	5.23	5.9	0.3
	Isoleucine	1.09	0.51	2.35	2.12	5.2	6.2	0.83
	Leucine	2.34	1.38	3.88	4.90	10.93	8.4	1.13
	Lysine	1.73	0.62	2.98	7.9	7.73	7.52	0.98
	Methionine	0.44	0.07	0.86	0.63	3.11	3.73	0.75
	Phenylalanine	1.03	0.33	2.24	0.72	5.76	4.93	1.06
	Threonine	1.20	0.27	1.67	3.55	5.57	5.45	0.94
	Tryptophan	0.29	0.27	0.27	0.95	4.74	4.45	0.25
	Valine	2.01	0.14	3.50	4.62	6.23	6.65	0.94
Non-essential amino acids (g/100 g)	Alanine	2.79	2.86	4.69	4.02	7.15	5.35	0.55
	Aspartic acid	3.17	0.51	2.87	8.64	9.85	9.56	0.83
	Arginine	2.00	1.62	3.47	3.02	6.95	6.45	1.75
	Cysteine	0.28	NR	0.38	0.74	NR	NR	NR
	Glutamic acid	3.84	2.16	6.77	2.41	16.56	17.85	1.09
	Glycine	1.55	3.47	3.31	3.64	7.41	6.45	0.61
	Proline	1.75	0.62	2.81	1.26	4.45	4.24	0.49
	Serine	1.86	0.80	1.32	0.61	5.65	3.65	0.45
	Tyrosine	3.29	0.01	2.77	5.44	4.74	4.45	0.19
	References	(Köhler, Kariuki, Lambert, & Biesalski, 2019)	(Hall et al., 2017)	(Udomsil et al., 2019)	(Bednářová et al., 2014)	(Mohammed et al., 2020)	(Mohammed et al., 2020)	(Mohammed et al., 2020)

(NA: Not applicable, NR: Not reported).

acids ranged from 21.8 to 23.7 g/100 g of the sample, which were 2 times higher than the recommended amounts (12.7 g/100 g of sample on DWB) for adults according to FAO, UNO, and WHO. The nutritional composition of some main edible species of crickets (average amounts present in dried powder or flour form) has been described in Table 1.

3. Food applications of edible crickets

The consumption of edible insects, in general, and in the case of the house cricket, is gaining more and more weight worldwide, it has become necessary to start issuing regulations to guarantee the safety of consumers, some countries have already begun to issue regulations in this regard. Thus, recently the European Commission authorized the inclusion of the partially defatted powder of common house cricket in the European Union's list of novel foods established in Implementing Regulation (EU) 2017/2470, authorizing its use throughout the EU for the manufacture of food products (European Commission, 2023; Pilco-Romero et al., 2023). Meanwhile, Canadian regulations state that if there is historical documentation of the traditional consumption of a type of food in another place in the world, it can be sold in Canada without further regulations, but first, it must undergo the novelty determination process (Larouche, Campbell, et al., 2023). Due to this, several species of edible insects are already considered non-new foods, including common house cricket, for which the Canadian government has declared that this "ingredient has a history of safe use as a food" (Government of Canada, 2022). In the United States, the management of insect food is regulated by the direction of the US Food and Drug Administration (FDA). The cultivation of insects for human consumption must follow good manufacturing practices (cGMP, 21CFR110). Insects raised for animal feed cannot be used for human consumption, just as insects collected from the wild cannot be sold for food. If insects are not marketed as such but are modified or used as an ingredient in food formulations, authorization as a food additive may be required. An insect protein is considered a food additive unless it has GRAS (Generally Recognized as Safe) status (Lahteenmaki-Uutela et al., 2017; Pilco-Romero et al., 2023).

Ensuring food security, particularly in developing countries, requires collaborative efforts from all stakeholders to guarantee an adequate supply of food that is both high in quality and quantity for everyone. While existing protein sources are insufficient to meet the requirements of the ever-growing human population in the future, increased research is required to utilize less expensive sources of nutrients to combat hunger and malnutrition. Among the various feasible options, edible insects present an attractive choice as a source of cheap and highly bioavailable protein (Barsics et al., 2017; Oibiokpa et al., 2018; Haber et al., 2019). The consumption of common house cricket depends on its distribution and cultural traditions surrounding insect consumption in certain populations. Traditionally, the common house cricket has been part of the diet of countries in Africa, Asia, and Oceania. Yet currently, its consumption has spread to countries with markets that have resisted food defined as "unconventional," as is the case in Europe and America (Pilco-Romero et al., 2023). The potential of common house cricket and other edible cricket species as ingredients for the development of protein-enriched foods is described below in detail.

3.1. Supplementation of diets

Studies have evaluated the potential of cricket protein for supplementation of various diets. Oibiokpa et al. (2018) determined the protein quality of termites, caterpillars, crickets, moths, and grasshoppers, as well as the effects of diets supplemented with the above-mentioned insects on hematological and biochemical indices in rats. Standard analytical methodologies were used to find out the amino acid composition of the insects. On a 10% protein basis, 5 isonitrogenous and isocaloric diets containing insects and casein were produced. As a control, a nitrogen-free diet was designed. In comparison to other insect proteins studied, cricket has an amino acid score of 0.91, a biological value of 93.02%, a net protein ratio of 3.04, a protein efficiency ratio of 1.78, and protein digestibility-corrected amino acid score of 0.73. The body weight ratios of liver, spleen, lung, and heart for those rats that were fed diets supplemented with edible insects were not significantly different ($p > 0.05$) from those that were fed basal and casein diets. In another study, Zielińska, Karaś, and Baraniak (2018) investigated the functional properties of tropical house cricket, dessert locust (*Schistocerca gregaria*), and yellow mealworm (*Tenebrio molitor*), as 3 edible insect species and compared them with casein (milk protein). The solubility, EAs, FCs, oil holding capacity (OHC), and water holding capacity (WHC), were assessed. At pH 5, protein solubility is at its lowest value. The protein preparation value for yellow mealworm was 3.95 g/g with the highest WHC and 3.33 g/g for tropical house cricket with the highest OHC. The protein of tropical house cricket exhibited the best EA of 72.62%, FC of 99%, and foam stability (FS) of 92% while the protein of dessert locust had the best emulsion stability (ES) of 51.31%. In another research, Kinyuru, Kipkoech, Imathiu, Konyole, and Roos (2021) made a cereal-cricket porridge (that was nutrient-dense and could be used in Kenyan school feeding programs) and assessed its acceptability and safety in comparison to porridges that were made from cereal and milk. Extrusion cooking was used to process 3 porridge flours M10 (millet, milk powder & maize), MM (millet & maize), and C5 (millet, cricket powder & maize) to meet the necessary needs of nutrition of children aged between 3 and 5 years. The children were given 300 mL of M10, MM, and C5 porridges during the school days for 4 weeks. Porridge consumption was measured daily. The consumption of 50% porridge was rated as least acceptable, 50 to 75% was rated as moderately acceptable, and >75% consumption was rated as highly acceptable. The results revealed that the porridge flours developed from the above-mentioned combinations provide essential micro and macronutrients to children aged between 3 and 5 years.

3.2. Development of meat analogs

Hall, Johnson, and Liceaga (2018) hydrolyzed the topical house crickets for time durations of 30, 60, and 90 min with alcalase concentrations of 0.5, 1.5, and 3% (*w*/w) and assessed the FCs, emulsifying capacities (ECs), degree of hydrolysis (DH), solubility, and composition of amino acids. As compared with the control group that contains no enzyme, peptides were produced because of hydrolysis with DH ranging from 26 to 52%. The protein solubility of hydrolysates was improved by increasing the pH values. >30% of soluble proteins were obtained at a pH ranging from 3 to 7 and 50–90% of soluble proteins were obtained at the alkaline pH. The results revealed that the hydrolysates of cricket protein had the potential to be used as a functional alternative protein in the formulation of food ingredients. In another research, Kiiru et al. (2020) studied the effects of cooking temperature, inclusion levels of CF (0, 15, 30, and 45%), and water flow rate (WFR) on a texturized meat analog. The addition of CF and cooking temperature both have significant effects on tensile stress (both perpendicular and parallel), whereas WFR has no effect. At both WFRs, the tensile stress decreased with the addition of CF but increased with temperature. Fibrous meat analogs were obtained with high anisotropic indices (AIs) up to 2.80, especially at 10 ml/min WFR and 30% low-fat CF inclusions. Full & low-fat CFs at inclusions of 15 and 30% can partially substitute soy protein isolate (SPI) in the production of fibrous meat analogs.

Kim, Setyabrata, Lee, Jones, and Kim (2017) performed research to see how adding the flour of house crickets affected the textural and physicochemical characteristics of different formulations of meat emulsions. Gel-forming capacity (GFC), water absorption capacity (WAC), EC, and protein solubility of CP made from house crickets were determined at NaCl concentrations ranging from 0 to 2.10 M, and pH ranged from 2 to 10. 20% of back fat, 60% of lean pork, and 20% of ice were used in meat emulsion as a control group. Emulsions were made as 6 treatments with flour of house crickets that were spray-dried, and it replaced back fat portions at a level of 10% and replaced lean pork at a level of 5% based on total sample weight. NaCl and pH concentrations had significant impacts on the protein solubility (67 g protein/100 g) of the flour of house crickets. At NaCl concentrations ranging from 0 to 2.10 M. The results indicated that the meat emulsions can be fortified with protein as well as with potassium, phosphorus, and magnesium as micronutrients by the replacement of 10% fat portion meat and lean meat with flour of house crickets. In terms of textural properties, the replacement of lean meat/fat portion with CF led to an increase in the hardness ($P < 0.001$) of meat emulsion. The findings of the concerned study indicated that CF did not contribute to soft texture in low-fat emulsified meat emulsions. In another study, Smarzyński et al. (2019) investigated the impacts of 2%, 6%, and 10% additions of CP on the

Table 2
Development of nutritious food products by the addition of edible crickets.

Cricket specie used under study	The processed form of cricket	Treatment conditions	Desired product obtained	Characteristics observed	Sensory remarks of the product	Key findings	References
Common house cricket	CF	CF = 100 g NaCl = 2 g Tap water = 52.4 mL	Protein-enriched chapatti (roti)	Significant baked chapatti's textural properties	Data not found	Improved nutritional and functional characteristics	(Khatun, Van Der Borght, Akhtaruzzaman, & Claes, 2021)
	CP	0%, 10%, 20% of total WH was replaced with CP.	Protein-enriched bread	Increased stability of dough. Textural and nutritional properties enhanced	Data not found	CP had a great impact on the gluten network	(Perez-Fajardo, Bean, & Dogan, 2023)
	CP	CP = 10% and 30%.	Protein-enriched bread	Better nutritional value	Lowest average values of global liking with 30% CP.	Intermediate average values of global liking with 10% CP	(Osimani et al., 2018)
	CP	Cricket, lentil and buckwheat powders (10% and 20%)	Gluten-free bread	10% CP led to a 40% increase in protein content	Data not found	Acceptable technological properties	(da Rosa Machado & Thys, 2019)
	CF	Wheat flour = 1 kg Salt = 1.5%, yeast = 2% Fresh water =56%	Bread	Significantly more intense color	Data not found	5% edible CF had no negative impact on bread quality.	(Bartkiene et al., 2022)
	CF	Control and cricket-enriched doughs	Gluten-free sourdough bread	Typical flavoring profile	Data not found	A significant increase in the antioxidant activity of bread	(Nissen et al., 2020)
	CF	Wheat flour = 280 g Margarine = 100 g Saccharose = 50 g Vanilla sugar = 3 g Eggs = 50 g	Protein-enriched wheat biscuits	CF reduced the values of lightness, redness, and yellowness.	The highest intensity of emotion "angry"	Nutritional and functional characteristics enhanced	(Bartkiene et al., 2023)
	CP	CF = 5 g/100 g, 10 g, 15 g Sour cream with 12% fat content, salt, BP, and unsalted butter.	Protein-enriched oat biscuits	Protein content of the flour mixture increased from 9.48 g/100 g to 11.22 g/100 g	Highest liking values	10 g and 15 g CF can be labeled as a source of protein.	(Biró et al., 2020)
	CP	Replacing WF with CF at concentrations of 2%, 6%, and 10% (*w*/w).	Protein-enriched shortcake biscuits	50 g of CP provided carbohydrates 14%, proteins 8%, energy 12%	Significant reduction in the consumer acceptance	Functional, nutritional, and physical properties improved	(Smarzyński et al., 2021)
	CF	Bananas, eggs, and CF were added	Protein-enriched muffins with good taste	CF have more protein and calcium APF. CF muffins have more total fat and calories than APF	The taste testing protocol did not randomize	CF muffins are more delicious and nutritious as compared to APF muffins.	(Burt et al., 2020)
	CP	50% of CP was added to wheat flour	Pancakes	Increase in the following mineral elements: iron (0.7–1.2 mg/100 g), zinc (0.7–3.4 mg/100 g), and calcium (41.7–61.9 mg/ 100 g).	Data not found	Increase in Zn content by 92–107%	(Kosečková et al., 2022)
	CP	CP (0% (control), 5%, 7.5%, and 10%)	Chocolate chip biscuits	CP had a protein digestibility of 87.7%.	No differences in overall liking scores among samples made with 7.5% and 10%.	WF functional and rheological properties improved	(Aleman, Marcia, Pournaki, & Fernandez, 2021)
	Cricket protein hydrolysate	20% w/w cricket protein hydrolysate.	Tortilla	Elastic and pliable structure	Acceptability (scores>6.0)	Contained all essential amino acids including 40% of the daily lysine requirement.	(Luna, Martin-Gonzalez, Mauer, & Liceaga, 2021)
	CP	*Triticum durum* semolina and CP were added.	Protein-enriched wheat pasta	Significant increase in protein content, from 9.96% to 16.92%.	Better texture, clear foreign flavor and dark color contributed to the lower scores.	Improved culinary, protein and mineral content.	(Duda, Adamczak, Chelminska, Juszkiewicz, & Kowalczewski, 2019)
	CF	CF = 0 g CF = 6.25 g CF = 12.5 g	Protein-enriched buns	6.25 g of CF were preferred over those with 0 g and 12.5 g of CF.	CF-based buns obtain greater market shares than standard buns.	A demand-driven and viable way for improving food security	(Alemu, Olsen, Vedel, Kinyuru, & Pambo, 2017)
	CF	whole WF, BP, purified drinking water, tomato sauce, edible CP	Protein-enriched pita chips	Pita chips with CP have good taste, aroma, and flavor.	A lower aroma liking scores for all the treatments,	Fulfill protein deficiency in diets.	(Gurdian, Torrico, Li, & Prinyawiwatkul, 2022)

(continued on next page)

Table 2 (*continued*)

Cricket specie used under study	The processed form of cricket	Treatment conditions	Desired product obtained	Characteristics observed	Sensory remarks of the product	Key findings	References
	CF	(Control 0%, CF 2.5% CF 5.0%, and CF 7.5%).	Meat replacer in frankfurters.	The highest ($p < 0.05$) protein content of 17.87 g/100 g was found in the CF7.5 treatment.	CF2.5 treatment showed no significant differences in sensory parameters	No effect on the structural characteristics, Best alternative for using edible insects	(Cavalheiro et al., 2022)
	CF	0%, 2%, and 4% of CF were added to sausages.	Sausages	A substantial rise ($p < 0.05$) was noted in protein content.	Positive sensory evaluation	The overall quality of the sausages was improved	(Pavelková, Haščík, & Čech, 2022)
	Cricket protein powder	soy, cricket, and egg albumin (3 and 5%) with the addition of potato powder.	3D printed personalized meat	The index of viscosity and consistency was improved by raising the quantity of protein.	Data not found	The addition of cricket protein increased the storage modulus (G′), loss modulus (G″), and stress (τ_0).	(Mirazimi et al., 2022)
	CP	Pea powder = 0, 5, 10, and 15% CP with different water-to-protein ratios (0,1, 2, and 3)	3D printed personalized meat	Greatest fidelity prints and water-to-protein ratios of 2 and 3.	Data not found	Design space offers valuable trade-offs for enhancing user satisfaction and promoting health.	(Chirico Scheele, Hoque, Christopher, & Egan, 2021)
	CP	CP, cacao, and other flour.	Chucula as a traditional dairy beverage	A significant rise ($p < 0.05$) in crude protein content was noticed	Highly acceptable.	The nutritional quality of the chucula was improved	(Curado et al., 2021)
	CP	Probiotics, cricket powder and pre-treated by different processes.	Protein-enriched fermented beverage	ultrasound-assisted γ-irradiation (US-IRE) enhanced the solubility of cricket proteins and increased both their surface and total sulfhydryl group content.	Data not found	(US-E) and US-IRE induced much higher positive effects on improving the digestibility of fermented (F) beverages.	(Dridi et al., 2021)
Topical house cricket	CF	2%, 6%, and 10% (w/w) of insect flour by the replacement of an equal amount of WF.	Protein-enriched muffins with high biological value	content of protein increased proportionally as the amount of flour added increased.	Data not found	Nutrient-dense, soft, good texture muffins. Reduced the glycemic index,	(Zielińska, Pankiewicz, & Sujka, 2021)
	CP	Sugar = 11.6% Whole WF & CP =46.6% of corn-starch = 1.6%, soybean oil =16.3%	Protein-enriched whole-wheat snack crackers	15% CP made thin & crispy snack crackers with good texture and appearance.	15% WF with CP, remained 'acceptable.'	insect-based snacks may be halted on the basis of appearance.	(Ardoin, Marx, Boeneke, & Prinyawiwatkul, 2021)
	CF	Betty Crocker fudge chocolate brownie batter is mixed with WF, ECP	Protein-enriched chocolate brownies	Males more likely than females to purchase and consume	For all the sensory attributes studied (except appearance), liking moment altered.	ECP in Western diets is beneficial.	(Gurdian, Torrico, Li, Tuuri, & Prinyawiwatkul, 2021)
Two-spotted cricket	CP	tapioca flour =10% w/w, cricket powder = 10%, and/or mango peel powder = 10%	Fermented rice noodles	Altered the color of the fermented rice noodles.	highest expected sensory-like score.	The overall of the rice noodles was improved by the addition of CP.	(Maw, Sae-Eaw, Wongthahan, & Prinyawiwatkul, 2022)
Jamaican field cricket	CP	CP (0, 5, 10, and 15%).	Sauce	15% CP was more adhesive and firmer as compared	A significant overall liking and purchase intent with 5% CP.	The nutritional quality was improved	(Fernandez et al., 2022)

CF: cricket flour, WF: wheat flour, OF: oat flour, APF: all-purpose flour, BWF: buckwheat flour, CP: cricket powder, ECP: edible cricket powder, BP: baking powder, NaCl: table salt- sodium chloride.

consumer acceptance and nutritional composition of pates. The addition of CP increased the minerals, fat, and protein contents. The addition of CP improved the texture according to consumer ratings. According to the feedback given by consumers, the product with only 2% CP addition had a high consumer appeal.

Cavalheiro et al. (2022) investigated the use of CF (purchased from the UK market) in frankfurters as a meat replacer and its impact on nutritional, technological, structural, and sensory characteristics. Four treatments were prepared with different concentrations of CF (Control, CF2.5, CF5.0, and CF7.5). There was a significantly high protein content in treatments with CF addition but without change in the fat content. The CF7.5 treatment showed significantly high PUFA contents, but there was no significant impact on MUFA content, compared with the control treatment. The CF significantly improved the contents of zinc, calcium, and manganese but not that of sodium. The processing loss of reformulated frankfurters was significantly reduced. The CF2.5 treatment appeared to be the best alternative for using edible insects in frankfurters.

3.3. Development of protein-enriched bakery products

CF was used as a protein source in the design of gluten-free sourdough slices of bread for celiac patients. Nissen, Samaei, Babini, and Gianotti (2020) made fermented doughs by using different methods, and volatile compounds, antioxidant activity, the relationship of pH with microbial growth, and protein profile were analyzed and compared with gluten-free slices of bread that were taken as a standard before and after baking. The fermentation processes of standard dough and dough made by the addition of CF are the same. 1-hexanol, nonanoic acid, 1-heptanol, 3-octen-2-one, and 2,4-nonadienal expressed in different amounts, conferred to a specific flavoring profile of the slices of bread, characterized by a unique combination of the above-mentioned volatile compounds. Antioxidant activities were significantly increased in cricket-enriched slices of bread, indicating that CF improved the antioxidant potential and nutritional status of gluten-free bakery items. In another study, da Rosa Machado and Thys (2019) made gluten-free bread with the addition of CP. Compared to the control bread (without CP), all the enriched slices of bread have harder and chewier crumbs. When canola oil is removed from bread formulations, breads with the same characteristics as the control sample were produced. When CP was added at 10%, it increased the nutritional value of the loaves in terms of protein by 40% and when it was added at 20%, it increased the protein value of the loaves by 100%. Other protein-enriched bakery products that were developed by using CF or CP are described in Table 2.

3.4. Bio-preservation potential

Cricket protein hydrolysates can be used for the bio-preservation of other foods including dairy and animal-based meat products. Recent investigations on the bio-preservation potential of cricket protein hydrolysates are described below:

Lone et al. (2023) processed the cricket protein samples obtained from common house crickets with microwave and ultrasonication, developed cricket protein hydrolysates by using 3% alcalase enzyme, and investigated their effects to improve the stability of cheddar cheese during storage. Cricket protein hydrolysates were freeze-dried and added to the cheese samples up to the maximum level of 1.5% and quality parameters were analyzed after 3 months of storage at 4 °C. The results showed that the pre-treated cricket protein hydrolysates significantly improved the lipid stability, antioxidant potential, and sensory attributes of the cheddar cheese and controlled microbial growth during storage. In another study, Lone et al. (2023) also performed research on goat meat emulsion to evaluate the bio-preservation potential of cricket protein hydrolysates developed from common house crickets. Cricket protein was hydrolyzed by using 3% alcalase enzyme and the preservation potential and functional properties of the cricket protein hydrolysates were enhanced by pretreatment with microwave and ultrasonication techniques. The hydrolysates of cricket protein were added to samples of goat meat emulsion and quality parameters were analyzed after 2 weeks of storage at 4 °C. The results indicated that the lipid stability, antioxidant potential, and sensory characteristics of the goat meat emulsion were improved by the addition of cricket protein hydrolysates, and they also showed antimicrobial properties. The functional value of the goat meat emulsion was increased by an increase in ion-reducing and radical scavenging activities because of the digestion simulation process.

3.5. Negative effects of edible crickets' incorporation on sensory characteristics

Kiiru et al. (2020) developed a texturized meat analog by the addition of CF and soy protein isolate (SPI) in which the inclusion of CF was correlated negatively with parallel and perpendicular tensile stresses because CF contains a significant amount of dietary fiber and chitin content that got embedded in the protein phase and may prevent the unfolding and aggregation of protein molecules, thus forming the weak structure. Kim et al. (2017) developed meat emulsions by the addition of CF obtained from common house crickets and indicated that the secondary parameters of treatment emulsions, gumminess ($P = 0.001$), and chewiness ($P < 0.001$), were significantly increased. The substitution of animal fat with ingredients incorporating additional water creates low-fat emulsified meat products with softer and less resilient/elastic textures, which leads to major quality issues in these products. Smarzyński et al. (2019) developed pates by the addition of CP at 2%, 6%, and 10% and observed that it lowered the L* value of pates (makes it darker in color) and shifts the color balance towards blue color. It was shown that the CP additive affects the sensory characteristics of the enriched pâté. The reference product (without the addition of CP) had the highest rating in terms of appearance, compared to all enriched pâtés. The CP additive changed the color, which resulted in worse acceptance among consumers. A negative effect of the additive on the taste and flavor assessment was also observed. With the increase in the amount of CP additive, the palatability of meat and liver in taste and flavor decreased, while the saltiness and palpability of others taste, and flavor increased. In another investigation, Cavalheiro et al. (2022) developed frankfurters (a type of sausage) by utilizing CF and observed that reformulated frankfurters were brownish compared with the control, which affected the sensory scores of those treatments. No effect on the structural characteristics of frankfurters was observed. The replacement of pork meat with CF resulted in changes in the hardness, cohesiveness, springiness, and chewiness of frankfurters. The addition of CF increased the hardness of frankfurters compared with the control treatment ($p < 0.05$). Consequently, the chewiness was significantly increased ($p < 0.05$) in treatments with 5.0% and 7.5% pork meat replacement. On the counterpart, cohesiveness and springiness decreased ($p < 0.05$) with the addition of CF, probably due to the greater swelling capacity of the CF. The poor scores for the appearance and color attributes of frankfurters with CF additions may be due to the brownish-colored appearance, and the scores for texture may be due to the hard texture, which is unlike the frankfurters that consumers were familiar with. Regarding taste, the panelists reported a bitter taste and aftertaste in the CF7.5 treatment.

4. Safety aspects

Edible crickets are a rich source of proteins, minerals, and essential oils but it is important to assess the chemical and microbial hazards as well as allergens associated with them before recommending them as a safe food for consumption. The studies and assessments on chemical and microbial risks and the allergens associated with edible crickets are described below in detail.

4.1. Hazards

Turck et al. (2022) performed research in a panel as per the request of the European Commission to evaluate the chemical and microbial hazards associated with defatted powder made from house crickets. The results showed that defatted CP had Cd (<0.025 mg/kg), Hg (<0.02 mg/kg), As (<0.1 mg/kg), and Pb (<0.1 mg/kg) as heavy metals, AFB1 (<0.1 mg/kg), AFB2 (<0.1 mg/kg), AFG1 (<0.1 mg/kg), AFG2 (<0.1 mg/kg), FB1 (<100 mg/kg), FB2 (<100 mg/kg), DON (<10 mg/kg), ZEN (<10 mg/kg), and OTA (<0.5 mg/kg) as mycotoxins, PCDDs (<0.04 pg/g fat) as dioxins, *Enterobacteriaceae* (≤ 100 cfu/g), *Escherichia coli* (≤ 50 cfu/g), *Bacillus cereus* (≤ 100 cfu/g), and *Staphylococcus* (≤ 100 cfu/g) as microbes that are in low amounts to cause any health hazard. The panel concluded that the defatted CP is safe for the proposed uses. In another study, Fernandez-Cassi et al. (2020) investigated how different feeds affected the populations and microbial loads in common house crickets. Crickets were fed with late-cut fresh red clover hay, early-cut red clover hay, and controlled feed for 62 days as 3 different diets. Overall, raw crickets, total aerobic count (TAC), and *Enterobacteriaceae* numbers varied between 7 and 8 log cfu/g. The foodborne

Table 3
Hazards associated with whole crickets and cricket-based products.

Products	Heavy metals (mg/kg)	Mycotoxins (μg/kg)	Dioxins (pg/g fat)	Pesticides (mg/kg)	Microbes (cfu/g)	References
CP	• Cd <0.025 • Hg <0.02 • As <0.1 • Pb <0.1	• AFB1 <0.1 • AFB2 <0.1 • AFG1 <0.1 • AFG2 <0.1 • FB1 <100 • FB2 <100 • DON <10 • ZEN <10 • OTA <0.5	• PCDDs <0.04	-	• *Enterobacteriaceae* (presumptive) ≤ 100 • *Escherichia coli* ≤ 50 • *Bacillus cereus* (presumptive) ≤ 100 • Coagulase-positive *staphylococcus* ≤ 100	(Turck et al., 2022)
Insect samples containing whole crickets, CB, CF, and CP	**Whole crickets** • As= 0.28 • Cd= 0.094 • Pb= 0.032 • Hg= 0.018 **CB** • As= 0.16 • Cd= 0.23 • Pb= 0.059 • Hg= 0.0056 **CF** • As= 0.059 • Cd= 0.099 • Pb= 0.024 • Hg= 0.0011 **CP** • As= 0.34 • Cd= 0.058 • Hg= 0.028	-	-	Insect samples containing crickets: • Glyphosate= 0.15 • AMPA= 0.45 • Chlorfenapyr= 0.20 • Chlorpyrifos= 0.014 • Ethoxyquin= 0.055 • Trifloxystrobin= 0.0088 • Tris (chloropropyl) phosphate= 0.18	• *Salmonella* & *E. coli* >100	(Kolakowski, Johaniuk, Zhang, & Yamamoto, 2021)
CF	-	-	-	-	• *Escherichia coli* <1.63 • *Bacillus cereus* (1.88) • *Enterococcus* (1.65) • *Clostridium perfringens* (1.64) • *Staphylococcus* (1.70) • Yeasts and molds (1.64)	(Fröhling, Bußler, Durek, & Schlüter, 2020)
Cereal-cricket porridge flour	-	-	-	-	• Yeast and molds (1.7×10^2)	(Kinyuru et al., 2021)
Heat treated crickets	-	-	-	-	• *Enterobacteriaceae* <1.5 • Endospores (2.4) • Fungi <2.0	(Vandeweyer et al., 2018)
Frozen crickets	-	-	-	-	• *Enterobacteriaceae* <1.0 • Endospores (2.0) • Fungi <2.0	
Oven-dried crickets	-	-	-	-	• Enterobacteriaceae <1.0 • Endospores (2.4) • Fungi <2.0	
Smoked and dried crickets	-	-	-	-	• *Enterobacteriaceae* <1.0 • Endospores (3.4) • Fungi <2.0	

(CP: cricket powder, CF: cricket flour, CB: cricket bar, Cd: cadmium, Hg: mercury, As: arsenic, Pb: lead, AFB1: aflatoxins B1, AFB2: aflatoxins B2, AFG1: aflatoxins G1, AFG2: aflatoxins G2, FB1: fumonisin B1, FB2: fumonisin B2, DON: deoxynivalenol, ZEN: zearalenone, OTA: ochratoxin A, PCDDs: polychlorinated dibenzodioxins, AMPA: Aminomethylphosphonic acid)

pathogens i.e., *Bacillus cereus*, *Salmonella*, *Clostridium perfringens*, and *Listeria monocytogenes* were not found in any of the batches. Crickets fed with control feed had a mold count of 2.8 log cfu/g as a mean value, those fed with late-cut fresh red clover hay had a mean mold count of 4.5 log cfu/g, and those fed with early-cut red clover hay had a mean mold count of 4.2 log cfu/g. Proteobacteria predominated in crickets raised by early-cut red clover hay. Firmicutes predominated in crickets raised by late-cut fresh red clover hay, and *Proteobacteria* & *Firmicutes* predominated in crickets raised by the control feed. *Bacteroidetes*, *Proteobacteria*, and *Firmicutes* were found to be the dominant communities of bacteria. Safety hazards associated with common house crickets and related edible species of crickets are presented in Table 3 and Fig. 1.

4.2. Allergenicity

Consumption of insects may be associated with allergenicity and can

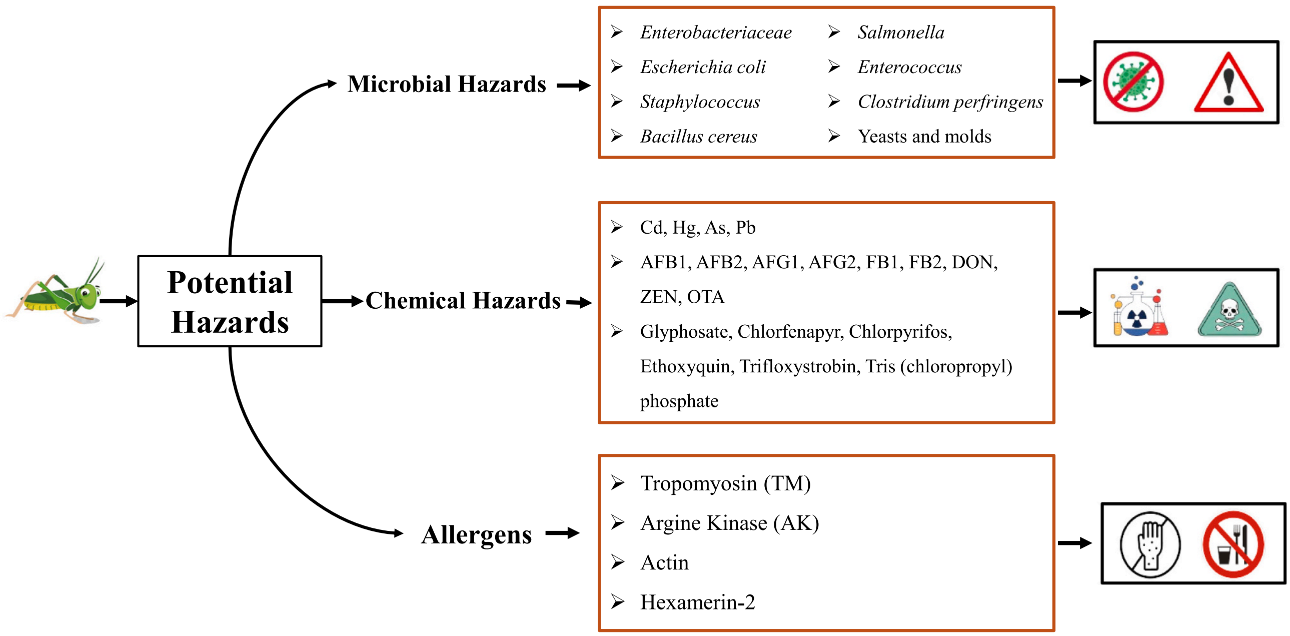

Fig. 1. Hazards associated with edible crickets and their flours.

pose a hazard to some vulnerable people. De Marchi et al. (2021) examined the immunoreactivity of house cricket and its cross-reactivity with white leg shrimp (*Litopenaeus vannamei*) after performing immunoblotting (an analytical technique used for the detection and characterization of proteins), along with the impact of cooking and digestive processes on their allergenic characteristics. Proteins separated by SDS-PAGE and 2-DE were electroblotted onto a 0.45 μm pore-size PVDF membrane at 80 V for 150 min. The membrane was blocked with 3% skimmed milk in PBS containing 0.05% Tween-20 (PT buffer) and incubated for 90 min with a mouse anti-tropomyosin polyclonal antibody (dilution 1:20000) or overnight with the patients' sera at 1:10 or 1:50 dilution. The most important IgE-binding protein was tropomyosin, and an enzyme-linked immunosorbent assay (ELISA) showed that it had cross-reactivity with tropomyosin of shrimp. The tropomyosin of house cricket remained unaffected during gastric digestion while tropomyosin of shrimp was not very stable during the process. As a result, the population of people who were allergic to crustaceans had serious concerns about consuming the proteins of house cricket. Francis et al. (2019) evaluated the cross-allergenicity of arginine kinase (AK) in several European nations in both whole insects and food formulations, in the light of the recent commercial availability of house crickets and mealworms. Oven-cooked insects, as well as purified AK fractions, were tested by the staff members of an entomology lab after the collection of sera from the above-mentioned insects. Immunoblotting against extracts of protein showed different allergic reactions of sera, according to the target species of insects. With AK as the main subject, low specific allergenicity was demonstrated and described the insects as safe for human consumption. Barre et al. (2021) thoroughly assessed the potential negative effects of edible insects including house cricket for people who had issues relating to food allergies. The variety of proteins found in commonly eaten insects, including the common house cricket, African migratory locust, red palm weevil, silkworm, yellow mealworm, and giant mealworm beetle was investigated using proteomic and bioinformatic analysis. Many proteins were comprised of protein allergens that were phylogenetically related to arthropod species of mollusks, insects, mites, and crustaceans. The chemosensory proteins, larval cuticle proteins, and odorant-binding proteins had similar three-dimensional (3-D) structures and well-conserved amino acid sequences, but they appeared to be absent in other groups of arthropods, especially in nematodes and mollusks. In another study, Kamemura et al. (2019) assessed the potential for allergic reactions in people with crustacean allergies who consume crickets. Using IgE crosslinking-induced luciferase expression (EXiLE) and ELISA, the risk of food allergies associated with the consumption of two-spotted crickets in patients with a previous history of shrimp allergies was assessed. The results indicated that people having a previous history of allergies to crustaceans may experience an allergic reaction after consumption of edible crickets. Therefore, before consuming cricket meals, shrimp specific IgE levels and allergy risks should be considered.

The allergenicity of the cricket proteins has been reported to be affected by thermal processing, such as microwaves, as well as by enzymatic hydrolysis. Hall et al. (2018) used alcalase to hydrolyze whole tropical crickets to a hydrolysis level ranging from 15 to 85%. Before and after simulated gastrointestinal digestion, dipeptidyl peptidase-4 (DPP-IV) inhibition of the cricket protein hydrolysates (CPH), antioxidant activity, and angiotensin-converting enzyme (ACE) were assessed. CPH with 60–85% DH showed greater ACE and DPP-IV inhibition. Human shrimp-allergic sera were used to assess the allergenicity of CPH. In the unhydrolyzed cricket and CPH with DH ranged from 15 to 50%, all sera responded positively to tropomyosin, whereas CPH with DH ranged from 60 to 85% showed no reactivity. In comparison to unhydrolyzed CPH that was taken as control, CPH with DH ranging from 60 to 85% had the lowest tropomyosin reactivity and highest bioactive potential. In a similar study, Hall and Liceaga (2020) assessed the inhibition activities of ACE and DPP-IV, as well as the IgG reactivity of tropomyosin in protein hydrolysates of edible crickets. The protein that was hydrolyzed by microwave radiation showed the greatest inhibition of ACE ($IC50 = 0.096$ mg/ml) and DPP-IV (0.27 mg/ml). Although IgG reactivity concerned with tropomyosin was present in all samples. The protein that was hydrolyzed by using microwave radiation had the lowest binding. Raman spectroscopy revealed the conformational changes that may be related to immunochemical reactivity, particularly in the regions of S—S and Amide *I*. Enzymatic hydrolysis carried out by using microwave radiations can be an effective technique for producing hypoallergenic bioactive peptides (with reduced immunoreactivity) from proteins of insects.

Bose et al. (2021) investigated the proteomes of the roasted, whole, and powdered cricket products using liquid chromatography-tandem mass spectrometry (LC-MS/MS). 8 protocols for protein extraction methods were compared with each other utilizing unique peptide

Table 4
Allergenic proteins in major food allergy groups.

Major food allergy groups	Allergenic proteins	Allergens	Amounts of allergens/ Molecular mass	Mechanism of allergy	Symptoms of allergy	Key findings	References
Eggs	Ovomucoid (OVM) Ovalbumin (OVA) Ovotransferrin (OVT) Lysozyme (LYS) Chicken serum albumin YGP42	Gal d1 Gal d2 Gal d3 Gal d4 Gal d5 Gal d6	11% egg white 54% egg white 12% egg white 3–4% egg white 40–60% egg yolk 40–60% egg yolk	Egg allergy involves two phases: the sensitization, production of immunoglobulin E (IgE) specific to the allergen; the second phase, the elicitation, release of mediators of the immune response	Swelling, Difficulty in breathing, Runny nose, Red eyes, Stomach pain	Proteins and glycoproteins in egg white trigger allergic reactions.	(Vapor, Mendonça, & Tomaz, 2022)
Fish	Parvalbumin	Seb m1 Onc m1 Sal s1 Sco s1 Thu a1 Cyp c1 Clu h1	2–3 mg/g 2–2.5 mg/g 1.9–2.5 mg/g 0.3–0.7 mg/g 0.01–0.05 mg/g 2.5–5.0 mg/g 3.8–5.7 mg/g	Absorption of antigens. After absorption, tolerance mechanisms, preventing IgE sensitisation development.	Hives Nausea, Stomach cramps, Runny nose, Headaches, Anaphylaxis, (less common)	Cause diverse symptoms, ranging from mild to severe.	(Dijkema, Emons, Van de Ven, & Oude Elberink, 2022)
Milk	α–Lactalbumin β–Lactoglobulin Bovine serum albumin Immunoglobulins αS1–casein αS2–casein β–casein k–casein	Bos d 4 Bos d 5 Bos d 6 Bos d 7 Bos d 9 Bos d 10 Bos d 11 Bos d 12	1–1.5 g/L 3–4 g/L 0.1–0.4 g/L 0.6–0.1 g/L 12–15 g/L 3–4 g/L 9–11 g/L 3–4 g/L	Binding of antibodies to surface of mast cells and basophiles, milk exposure triggers the "activation" phase, a rapid release of inflammatory mediators responsible for the allergic reaction.	Hives, Wheezing, Itching, Swelling, Coughing, Vomiting, Diarrhea, Abdominal cramps etc.	A high percentage of children and adults does not show circulating IgE and their skin prick test and serum specific IgE antibodies result negative	(Giannetti et al., 2021)
Nuts (Hazelnuts)	Bet v 1-like (PR-10)	Cor a 1	17 (Molecular mass, SDS-PAGE)	When IgE binds to the epitopes, the food is recognized as foreign by the immune system, and an allergic reaction occurs.	Abdominal pain, nausea, Diarrhea, Difficulty swallowing, Itching, runny nose. Anaphylaxis (less common)	Several food allergens have been identified from tree nuts. Their physicochemical characterization ranges from primary sequence analyses up to detailed structural analyses.	(Geiselhart, Hoffmann-Sommergruber, & Bublin, 2018)
	Profilin	Cor a 2	14				
	nsLTP	Cor a 8	9				
	Legumin	Cor a 9	40				
	Vicilin	Cor a 11	48				
	Oleosin	Cor a 12	17				
	Oleosin	Cor a 13	14–16				
	2S albumin	Cor a 14	12				
Nuts (Walnuts)	2S albumin	Jug r 1	15–16				
	Vicilin	Jug r 2	44				
	nsLTP	Jug r 3	9				
	Legumin	Jug r 4	–				
	Bet v 1-like	Jug r 5	20				
	Vicilin	Jug r 6	47				
	Profilin	Jug r 7	13				
Nuts (Pecan nuts)	2S albumin	Car i 1	16				
	Vicilin	Car i 2	55				
	Legumin	Car i 4	55.4				
Nuts (almonds)	nsLTP	Pru du 3	9				
	Profilin	Pru du 4	14				
	60 s acidic ribosomal prot. P2	Pru du 5	10				
	Legumin	Pru du 6	65				
Nuts (Cashew nuts)	Vicilin	Ana o 1	50				
	Legumin	Ana o 2	55				
	2S albumin	Ana o 3	14				
Nuts (Pistachio nuts)	2S albumin	Pis v 1	7				
	Legumin	Pis v 2	32				
	Vicilin	Pis v 3	55				

(*continued on next page*)

Table 4 (*continued*)

Major food allergy groups	Allergenic proteins	Allergens	Amounts of allergens/ Molecular mass	Mechanism of allergy	Symptoms of allergy	Key findings	References
	Manganese superoxide dismutase	Pis v 4	25.7				
	Legumin	Pis v 5	36				
Nuts (Brazil nuts)	2S albumin	Ber e 1	9				
	Legumin	Ber e 2	29				
Insects (Silkworm)	Silkworm protein	Arginine kinase Paramyosin 27-kDa glycoprotein	– – –	Primary allergic sensitization or more likely of IgE cross-reactivity with other taxonomically related allergenic species belonging to arthropods.	Skin rashes, Swelling, Shortness of breath, Dizziness, Stomach pain.	Individuals with an existing crustacean shellfish allergy may have allergic reactions upon consumption of insects.	(De Gier & Verhoeckx, 2018)
Insects (Mealworm)	Mealworms protein	Cockroach allergen-like protein	–				
		Hexamerin 1B precursor	–				
		Muscle myosin heavy chain	–				
		Predicted long form paramyosin	–				
		Putative serine proteinase trunctated	–				
		Putative trypsin-like proteinase	–				
		Tropomyosin 1, isoform A	–				
		Tropomyosin	–				
		Tropomyosin, partial	–				
		Larval cuticle protein A1A	–				
		Larval cuticle protein A2B	–				
		Larval cuticle protein A3A	–				
Insects (Locusts)	Locust protein	Arginine kinase	–				
		Enolase	–				
		GAPDH	–				
		Hexamerin	–				
		Pyruvate kinase	–				
Insects (Crickets)	Cricket protein	Arginine kinase	–				
		Hexamerin 1B precursor	–				
		Actin	–				
		Tropomyosin	–				
Insects (Grasshopper)	Grasshoper protein	Argnine kinase	–				

identifications and the total number of proteins. In total 20 putative allergens were found, 3 of which were proteoforms of AK. For the AK proteoforms, a multiple reaction monitoring mass spectrometry (MS) assay was performed and applied to a portion of the extracts. The extraction and food processing methods showed an impact on allergen abundance and detectability. In another study, Lamberti et al. (2021) studied the effects of two common methods of cooking i.e., frying and boiling on the ability of IgE to recognize proteins from 5 edible insects i.e., tropical house crickets, silkworms, mealworms, grasshoppers, and buffalo worm. 3 groups of Italian patients with allergies to house dust mites and shrimp were engaged in the study along with 2 individuals who had occupational allergies and food sensitivities to mealworms, these patients had never eaten insects before. The solubility of proteins changed because of thermal processing, causing a shift from water-soluble fractions to water-insoluble fractions. The results from LC-MS/MS and immunoblotting analyses revealed tropomyosin as a significant cross-allergen for patients with shrimp and house dust mite allergies whereas larval cuticle protein appeared to be a significant contributor to patients with primary mealworm sensitivities. Processing effects seemed to be specific for species of the insect under study, treatments applied, and the nature of protein present in them. Therefore, even after thermal processing, patients with allergies to house dust mites, shrimps, and mealworms should proceed with caution when eating insects including edible crickets. The allergenic proteins present in major food allergy groups are described in Table 4.

5. Conclusion, challenges, and future recommendations

Entomophagy is one of the feasible solutions to ensure food security and curb food hunger faced by third-world countries and the developing world where animal protein resources are limited or insufficient to meet human dietary requirements. Edible insects are rich sources of protein, oils, minerals, and other essential micronutrients and offer an efficient and economical way to fulfill nutritional deficiencies. Common house cricket and related edible species are good sources of essential amino acids and minerals including calcium, iron, zinc, sodium, potassium, manganese, and copper. They are also a good source of fatty acids including oleic, palmitic, and linoleic acids. Studies have used crickets as a whole or as ingredients to develop different food products including meat analogs, cereal porridges, and protein-enriched bakery pasta products. While crickets as a whole or in the form of food ingredients have a good nutritional value, they may be associated with chemical and microbial risks and may induce allergic reactions in some vulnerable people. However, in general, cricket-based diets and food products are safe for human consumption and cannot cause a health hazard if consumed within appropriate limits after efficient processing. People with allergy issues should avoid consuming cricket or insect-based foods.

Previous investigations revealed the challenge of harder texture, darker color, and off-flavor of the food products developed by the addition of CF which are unfavorable characteristics with low sensory scores. To overcome the challenge of undesirable textural changes, it is recommended to add CF after finely grinding and efficient processing. To improve the flavor profile of cricket-based products, a flavor masking technique can be used in which such ingredients can be added in addition to edible crickets that have a stronger flavor. Spices and seasonings can also be used to enhance the overall taste of cricket-based meat analogs. Regarding safety concerns and allergenicity, previous research lacks the application of efficient techniques to quantify the allergenic proteins present in cricket-based food ingredients. There should be a proper risk assessment of physical, chemical, and microbial risks associated with edible crickets and cricket-based products and allergy studies by employing efficient analytical techniques and in-vivo model investigations where applicable. It is also recommended to research advanced processing technologies to mitigate the risks and improve the color, flavor, and texture properties of cricket-based food products.

CRediT authorship contribution statement

Syed Ali Hassan: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Ammar B. Altemimi:** Writing – review & editing, Investigation, Data curation. **Adeel Asim Hashmi:** Writing – review & editing, Methodology, Data curation. **Sandal Shahzadi:** Methodology, Conceptualization. **Waqar Mujahid:** Resources, Investigation, Data curation, Conceptualization. **Ahsan Ali:** Writing – original draft, Resources, Data curation. **Zuhaib F. Bhat:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **Saima Naz:** Writing – original draft. **Ahmad Nawaz:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Gholamreza Abdi:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Rana Muhammad Aadil:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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