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Feasibility and Potential of Yellow Mealworm (*Tenebrio molitor*) Protein Incorporation in Food Matrices: Nutritional, Perceptual and Applications – A Narrative Review

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ABSTRACT

The global population is predicted to reach 9 billion by 2050, driving the pressing need to improve the sustainable food solutions that align with the Sustainable Development Goals (SDGs) and the climate agreement presented in Paris Agreement. Furthermore, the conventional animal-based protein sources, demand high resources and contribute to environment depletion, prompting the need for alternative protein sources. Although the interest in mealworm protein as an alternative protein source is growing, research focusing on its practical application in food products remains limited. Addressing this gap by exploring mealworm protein addition into food systems is key to advancing its development. *Tenebrio molitor* (yellow mealworm) has emerged as a promising solution for global protein deficits owing to its remarkable nutritional profile. It offers a significant amount of essential macronutrients comprising half of its dry weight, outperforms several traditional protein sources including poultry and marine animals. Also, its balance amino acid composition, particularly high in essential amino acids for instance lysine and leucine supports its significant as a complete protein for human consumption. In fact, its low in chitin concentration in the larval stage enhances both digestibility and bioavailability relative to its counterpart. These properties highlight mealworm as a nutrient-dense option and demonstrate their potential for integration info food matrices to address malnutrition and improve global food security. Consequently, advances in protein extraction methods, including enzymatic hydrolysis and microwave-assisted extraction, have significantly improved the functionality and sensory characteristics of mealworm protein. This review examined the feasibility and potential of incorporating yellow mealworm protein into various food matrices. Besides, the consumer perceptions and acceptability, the importance of education and strategic marketing to mitigate cultural biases and enhance the acceptance of insect-based foods were discussed. In addition, the scalability and versatility of mealworm protein which has led to innovative food products and the ability to tailor food products specialized dietary requirements, including texture-modified foods for the elderly were presented.

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1. Introduction

The urgent need for sustainable alternative protein sources has triggered an upward trend in research and exploration, with edible insects emerging a viable solution. This shift is primarily driven by the projections of the total global population that will reach approximately 9 billion by 2050 [1]. Consequently, this projection has amplified the need to fulfil the food demand, particularly animal-based protein, which comprises 40 % of the global demand. Also, one of the concerns associated with the rising number of world population is that the production of animal-based protein requires high resources and costs. Simultaneously, the need for secure meat production and protein-rich feed for livestock consumption also increases. Nevertheless, traditional protein sources originating from mammals, poultry, and aquatic animals need to be improved to meet the demands effectively [2]. Furthermore, due to the increased expenses of soy meal and fish meal, alongside environmental issues and diseases including transmissible spongiform encephalopathy (TSE), foot and mouth disease (FMD) and avian influenza, highlight the necessity of exploring alternative protein sources [2].

In this context, scientists, academics, and industry stakeholders are diligently exploring feasible solutions to address the global protein demand, with edible insects emerging as one of the promising answers. Figure 1 shows the bibliometric analysis, based on 231 publications retrieved from the Scopus database (2012–2024), which provides a detailed overview of research on edible insects. Using a threshold of five occurrences, 103 keywords were analysed, revealing distinct thematic clusters. The red cluster, dominated by the keyword "edible insects," highlights the central focus on insect-based food systems, with strong connections to "food security," "sustainability," and "processing," emphasizing their potential role as a sustainable alternative protein source. The blue cluster centres on "entomophagy" and consumer-related aspects, featuring keywords like "consumer behavior," "neophobia," and "novel food," reflecting research on consumer acceptance and barriers to adopting edible insects. The green cluster focuses on nutritional composition and the use of insects in animal feed, with terms such as "protein content," "amino acids," and "animal feed," highlighting studies on the environmental and nutritional benefits of insect-based feed. The yellow cluster explores physicochemical properties and processing, including keywords like "protein extraction," "functional food," and "physicochemical properties," indicating a focus on enhancing the quality and functionality of insect-derived products. The purple cluster emphasizes proteins and fatty acids, with keywords such as "nutrition," "proteins," and "fatty acids," showcasing research on the nutritional profiles of edible insects. In general, the analysis indicates an interdisciplinary field characterized by strong interconnections between sustainability, nutritional science, and consumer behavior. This highlights the growing interest of edible insects as a sustainable food source while identifying opportunities for product development, bioactive benefits, and strategies to improve consumer acceptance strategies.

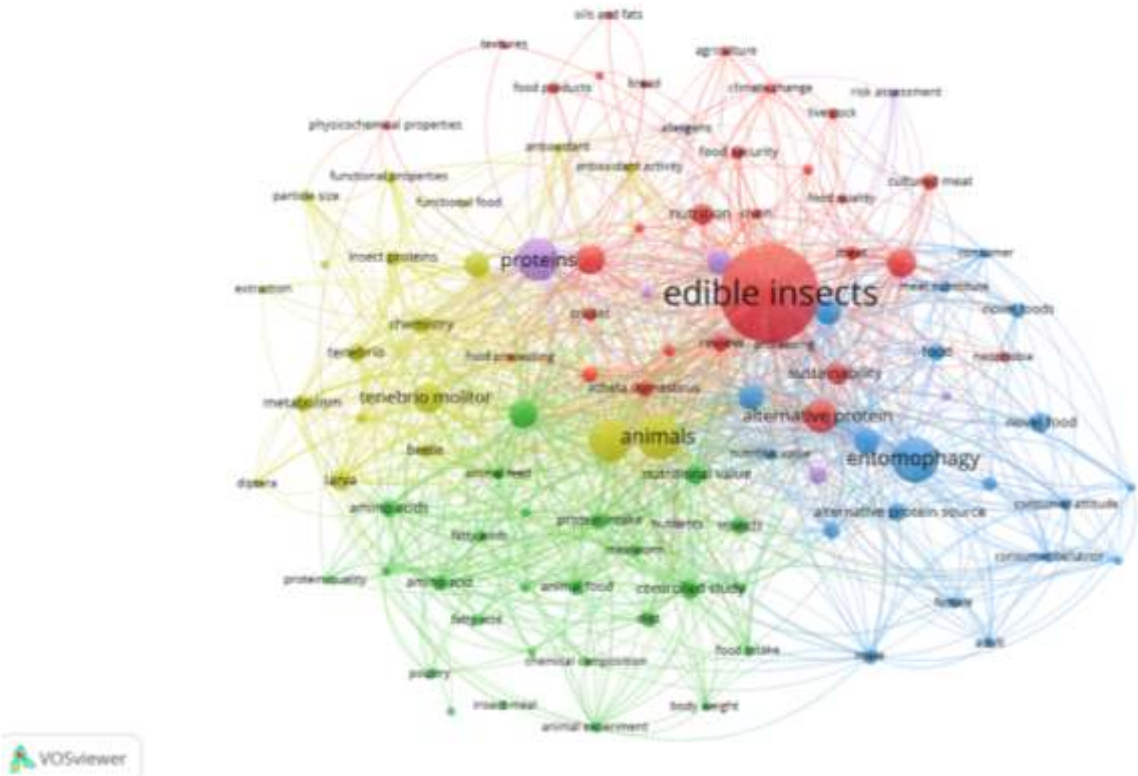

Fig. 1. Bibliometric network of edible insect and alternative protein studies (2012–2024)

Throughout the past decades, the trend of research on edible insects has evolved significantly, reflecting increased interest in their potential as a sustainable food and feed source. The bibliometric analysis demonstrates that this area covers a diverse array of interdisciplinary themes such as nutritional properties, functional applications, and consumer behaviour. Research on edible insects (Figure 1) has increasingly centred on the effort to support sustainable food systems, emphasizing their nutritional qualities, processing methods, and initiative to address global food security issues. Thus, entomophagy (consuming edible insects) is one of the possible substitutes that can offer a practical way to solve food security concerns [3]. Insects represent a significant portion of biomass on our planet and are becoming a valuable source of alternative protein for humans. Although entomophagy has become common in many areas, there is a noticeable reluctance among Western cultures to embrace this practice [4]. Insects can be considered as a rich source of nutrients, delivering considerable protein, healthy fats such as monounsaturated fatty acids, essential micronutrients and dietary fibre [5].

The Food and Agriculture Organization (FAO) strongly recommends entomophagy as a protein alternative [1]. This recommendation supports the cultivation and use of high macronutrient-dense edible insects such as mealworms to alleviate the global food security issues in protein demand [6]. Additionally, the practice of entomophagy is also beneficial as the cultivation of insects itself is high in agricultural efficiency, which uses lesser land, water, and feed than cattle. Consequently, this efficiency results in a substantial reduction in greenhouse gas (GHG) emissions and the overall environmental impact associated with traditional animal-based protein production, particularly in terms of their carbon footprint [7].

Apart from the previously mentioned benefits of entomophagy, edible insects like bees, butterflies, and beetles have drawn a lot of interest as promising alternative sources of protein, offering both nutritional value and sustainability. Munoz-Seijas *et al.,* [8] estimated that about 1,600 insect species are actively consumed globally. These insects were often favoured by the consumers for their high protein content, efficient feed conversion, ease of rearing, and minimal requirements for energy, water, and space. Furthermore, insects have a special ability to turn low-value organic waste into high-quality protein and other useful resources [72]. Among all the edible insects identified, the order of coleoptera, especially the yellow mealworm, stands out as one of the most extensively studied and consumed. This is owed to its sophisticated characteristics including high in nutritional value, ease of cultivation, and suitability for large-scale production [6,9-11].

Yellow mealworm larvae (*Tenebrio molitor or T. Molitor*) are considered highly valuable due to their significant protein content and relatively low chitin levels, which improve both protein digestibility and bioavailability [12]. The larval stage of *T. molitor* is commonly preferred, primarily due to its high protein concentration and lower levels of chitin, making it more suitable as a nutritional source compared to the adult stage [13]. Recent studies have highlighted the potential application of yellow mealworm protein in diverse food systems to enhance nutritional quality, sensory attributes, and consumer acceptability of the final products [14].

Moreover, mealworms are acknowledged as one of the most widely cultivated and commercially sold insect species. This Coleopteran insect, formerly thought to have originated in the Eastern Mediterranean, has since spread worldwide through colonization and trade [1]. This species is favoured for its rapid rate of growth, minimal rearing requirements, and ease of handling, making it a practical choice for large-scale farming operations. Notably, *T. molitor* is the sole insect among a group of seven that has been approved for sale as a novel food item under the European Commission Regulation 2021/1372, effective from August 17, 2021 [13]. *T. molitor* larvae have been reported to contain a high concentration of mono- and polyunsaturated fatty acids, nearly all forms of amino acids, significant ones (199 g/kg, dry matter), fat (18–40 %, dry matter) and protein (18–64 % dry matter) [15,16]. Owing to its favourable nutrient profile, mealworm positioned as a promising and sustainable alternative protein source, which also suggests that they also highly fits for the incorporation into food matrices.

Although the interest in mealworm protein as an alternative protein source is growing, research focusing on its practical application in food products remains limited. This gap is vital to address, more research focus on mealworm protein addition into food systems is key to its development. Beyond identifying its nutritional benefits, understanding and applying mealworm protein into various food matrices is essential to ensure the maximization of its potential. Furthermore, the limited studies on consumer acceptance, optimized processing methods, and nutritional profiling limits the industry's ability to scale and promote mealworm protein as a sustainable alternative. This review aimed to highlights the feasibility and practicality of incorporating yellow mealworm into several foods. It critically discusses the nutritional composition, consumer perspectives, and latent applications of mealworm protein in food products. The review emphasizes beneficial attributes of *T. molitor*, including its high protein content and reduced chitin levels throughout the larval stage, which enhance bioavailability and digestibility. Additionally, it analyses studies on the utilization of yellow mealworm protein to improve the nutritional and sensory characteristics, overall acceptability of food items, and future prospects of mealworm protein.

2. Entomophagy

Entomophagy primarily defines as the human consumption of insects, but it also encompasses the dietary intake of insects by all living species [17]. The term originates from the Greek words "entomon" and "phagy" and is well recognized in academic literature. The word "insectivory" is utilized when insects are consumed by non-human animals or certain carnivorous plants [17]. Recently, Neto-Costa and Dunkel [17] explained that the term "anthropoentomophagy" has been suggested as a more accurate term to describe human ingestion of insects and insect-derived products. Nonetheless, "entomophagy" remains the favoured term in academic discourse, specifically referring to the consumption of insects and allied arthropods, such as spiders and scorpions, by humans [17].

Neto-Costa and Dunkel [17] studied that humans globally consume insects from multiple groups, predominantly Coleoptera (19 families, 467 species), Lepidoptera (29 families, 296 species), Hymenoptera (6 families, 268 species) and Orthoptera (9 families, 219 species). Coleoptera and Orthoptera are notably prevalent at the species level, with Scarabaeidae (201 species) and Acrididae (150 species) representing the most often consumed families. Among Lepidoptera, the most consumed families are Saturniidae (86 species), Hepialidae (41 species) and Sphingidae (25 species). The principal edible families within Hemiptera include Cicadidae (52 species), Pentatomidae (27 species), Nepidae (9 species) and Belostomatidae (9 species). Table 1 shows the current scenario of insect farming regionally focus.

Table 1
Current scenario of insect farming: Regional focus

Region/Country	Number of insect farming companies	Key insects farmed	Key players/Details
Africa	~2,300 small-scale farms	18 edible insect species	Predominantly small-scale producers
Canada	At least 28 companies	Crickets, Mealworms, BSF	Entomo Farms, Aspire Food Group, Super Cricket Farms
United States	At least 11 cricket, 13 mealworm, and 10 BSF companies	Crickets, Mealworms, BSF	Beta Hatch, Chapul Farms, All Things Bugs, Innova Feed
Mexico	27 medium and large-scale companies	Crickets, Mealworms, BSF	Nutrinsectos, Aspire, Ynsect, Optiprot
Brazil	14 companies	Crickets, Mealworms, BSF	NS
Chile	7 companies	Crickets, Mealworms, BSF	NS
Argentina	5 companies	Crickets, Mealworms, BSF	NS
Costa Rica	5 companies	Crickets, Mealworms, BSF	NS
Colombia	4 companies	Crickets, Mealworms, BSF	NS
Peru	4 companies	Crickets, Mealworms, BSF	Demolitor
Guatemala	2 companies	Crickets, Mealworms, BSF	NS
Uruguay	2 companies	Crickets, Mealworms, BSF	NS
Cuba	1 company	Crickets, Mealworms, BSF	NS
Asia	NS	Crickets, Mealworms, BSF, Medicinal insects	Large-scale operations in China, Thailand, and Vietnam (Entobel, Hop Co.)
Europe	NS	Crickets, Mealworms, BSF	Predominantly industrialized farming (Alpha-Protein)

Note: NS= Not Specified; BSF=. Black Soldier Fly. Source: Rudy Caparros Megido *et al.,* [18]

In addition, a study by Omuse *et al.,* [19], in which analysed the global insect diversity and its implications for sustainable food systems revealed that the edible insect consumption varies significantly by region. The finding shows that Coleoptera and Orthoptera are among the most commonly consumed insects in Asia, North America, and Oceania, while Lepidoptera and Hymenoptera are more prevalent in Africa and South America. These regional preferences are shaped by the combination of cultural traditions and environmental factors. Asia, in particular, stands out for its diversity in insect consumption, with Coleoptera leading the way with 354 species, including mealworms, which belong to the Coleoptera family.

Meanwhile, other than consumer acceptance and willingness to practice entomophagy in their diet, one of the issues often discussed is the Halal perspective of the insect consumption. Recent developments in the Halal certification for the edible insects, as of 2024, the Islamic religious council Singapore (MUIS), has ruled a fatwa that concludes "food products derived from insects are generally permissible unless the insects are harmful or there is a specific ruling that clearly prohibits them."[20]. This ruling facilitates the possibility of edible-insects commercialization that target diverse group of consumers especially in the Asia region. It is not uncommon for some regions or countries to rule edible insects as Halal while others do not. This is due to such decisions require a thorough discussion that includes both religious and technical considerations to reach a consensus. Riyaz [21] highlighted that acceptance of insect consumption within Islamic dietary laws varies due to differing interpretations in Islamic jurisprudence. These differences stem from varying perspectives on whether insects are considered pure, nutritious, and culturally suitable, reflecting the diversity of thought within Islamic dietary practices, despite a shared agreement on the prohibition of impure or harmful foods.

Besides, the consumption of insects also has been associated with its benefits to health. This is owed to the high-quality macro and micronutrients which able to enhance overall health including the cardiovascular health and cognitive function [22]. Recently, it has been reported that the protein extracted from house cricket protein hydrolysate (HCPH) was found to be capable in alleviating hypertension and vascular health. A study by Sangartit *et al.,* [23] revealed that house cricket protein significantly lowered the blood pressure and improved the endothelial function of hypertensive rats with nitric oxide deficiency. The study revealed that in nitric oxide-deficient hypertensive rats, daily administration with HCPH at doses of 250 mg/kg and 500 mg/kg body weight (BW) resulted in a considerable reduce in blood pressure (BP). Additionally, the result also suggested the house cricket protein reduced the oxidative stress markers and improved vascular structure. Further demonstrates the health benefits of edible insects that can potentially be applied to human. Additionally, Oh *et al.,* [24] successfully demonstrated that mealworm protein, acquired through various extraction methods (alkaline, acidic, enzymatic and screw press) exerted a remarkable anti-inflammatory and anti-hyperglycaemic properties. The result shown that the screw-pressed concentrate (MP) had the highest essential amino acids (EAAs) content at 64.24 g/100 g protein, while the alkali-extracted (MA) contained 40.41 g/100 g, salt-extracted (MS) had 27.22 g/100 g, and enzyme-extracted (ME) showed 45.31 g/100 g protein. The MS significantly reduced tumour necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) levels with p-values < 0.05, indicating strong anti-inflammatory effects. Additionally, the ME exhibited a significant reduction in blood glucose levels ($p < 0.05$) and showed the highest antioxidant activity at 78.5% scavenging capacity in the DPPH assay, compared to 62.3% for MS and 54.1% for alkali-extracted protein (MA). Furthermore, the in vitro ileal digestibility (IVID) was highest for ME at 99.53% and MS at 99.47%, while MA had a significantly lower digestibility of 9.32%. The author recommended that mealworm protein capable in exerting blood glucose modulation, suggesting the potential of mealworm protein as a functional food ingredient for diabetic patient. Apart from health benefits, entomophagy also has a substantially smaller environmental impact due to its low in greenhouse gases (GHG) release than conventional cattle rearing, making it a potential option for solving global food security and sustainability concerns.

According to FAOSTAT, the data presented in Table 2 and 3 suggests that livestock production has consistently increased, particularly in species like camels (+17.21%) and ducks (+30.49%), reflecting global efforts to meet growing protein demands. However, this growth has led to a rise in greenhouse gas emissions, with methane and nitrous oxide emissions increasing notably from cattle (+4.52% and +5.00%, respectively) and goats (+7.5%). This highlights the environmental burden of conventional livestock systems and underscores the urgent need for alternative protein sources, such as mealworm. Mealworm protein offers a sustainable, low-emission solution, aligning with global goals to mitigate climate change while addressing the rising demand for protein. Integrating mealworm protein into food systems could provide a viable pathway toward sustainable and environmentally responsible food production.

Table 2
Estimate livestock production major source of protein worldwide

Livestock	Production (tones)	Period (year)	Production changes (%)
Mammals			
Buffalo	6,803,701.13 - 6,903,483.83	2018 – 2022	1.47
Camels	515,785.28 - 604,530.26	2018 – 2022	17.21
Cattle	66,074,787.46 - 69,346,116.17	2018 – 2022	4.95
Goats	5,889,989.65 - 6,367,497.20	2018 – 2022	8.11
Sheep	9,534,499.03 - 10,272,315.46	2018 – 2022	7.74
Swine	119,065,590.27 - 122,585,397.38	2018 – 2022	2.96
Poultry			
Chicken	114,567,848.72 - 123,631,334.72	2018 – 2022	7.91
Ducks	4,650,703.02 - 6,068,757.07	2018 – 2022	30.49
Turkeys	5,664,586.06 - 5,081,497.88	2018 – 2022	-10.29

Note: FAOSTAT [25]

Table 3
Estimate nitrous oxide and methane emission from major source of protein worldwide

Livestock	N20 (Nitrous Oxide) Emission, (kt)	CH4 (Methane) Emission, (kt)	Period (Year)	N20 Emission changes (%)	CH4 Emission changes (%)
Mammals					
Buffalo	213.51 – 214.91	11,892.26 – 12,148.40	2018 - 2022	0.65	2.15
Camels	29.83 – 34.60	1,745.41 - 2,024.77	2018 - 2022	16.01	16.01
Cattle (dairy)	497.38 – 502.49	20,456.72 - 20,616.95	2018 - 2022	1.03	0.78
Cattle (non-dairy)	1,683.88 - 1,768.01	55,395.99 - 57,902.54	2018 - 2022	5.00	4.52
Goats	364.28 - 391.43	5,513.36 - 5,928.48	2018 - 2022	7.46	7.53
Sheep	363.21 - 392.65	6,951.93 - 7,485.28	2018 - 2022	8.11	7.67
Swine	26.52 - 26.47	598.20 - 594.90	2018 - 2022	-0.22	-0.55
Poultry					
Chicken	210.35 - 225.33	322.70 - 346.64	2018 - 2022	7.12	7.42
Ducks	30.97 – 30.60	15.56 – 15.59	2018 - 2022	-1.20	0.19
Turkeys	15.35 – 14.87	17.59 – 16.48	2018 - 2022	-3.14	-6.34

Note: FAOSTAT [25]

Based on the information presented in Table 1, it can be observed that mealworms have emerged as one of the leading options of sustainable and versatile edible insects. This is due to their farming that only requires minimal resources, lesser land and evidently will result in lower greenhouse gas (GHG) emissions compared to the conventional livestock farming. In addition, the consumption of water is quite similar to chicken, but significantly less than pork or beef [6]. Furthermore, mealworms can provide an effective solution for waste management due to its ability in transforming food industry by-products into high-value protein, aligning with the principles of a circular economy (CE) [26]. Their exceptional nutritional value, efficient resource utilization, and versatility in various food applications position them as a key alternative protein source. As consumer demand for sustainable and functional ingredients continues to grow, mealworm larvae stand out as a practical solution to address global food security and environmental challenges. This makes them deserving of further detailed exploration, particularly in understanding their potential applications and benefits, as exemplified by *Tenebrio molitor* (yellow mealworm).

3. *Tenebrio molitor* (yellow mealworm)

Tenebrio molitor are highly regarded among edible insects owing to their outstanding nutritional composition, which translate into high levels of protein and fat, good digestibility, appealing flavor, and bioactive compounds like chitin and antimicrobial peptides (AMPs) [27]. They are easy to rear and maintain, with consistent protein content regardless of diet, making them ideal for stable production. As a result, *T. molitor* is widely farmed on an industrial scale to supply feed for pets, zoo animals, and livestock such as fish, pigs, and poultry [11].

T. molitor, a darkling beetle which is commonly found in the environments linked to flour, grain or food storage environments [8]. Figure 2 illustrates the classification of the yellow mealworm (*T. molitor*), categorizing it within the kingdom *Animalia*, which highlights its multicellular and eukaryotic nature [28]. It is further classified under the class *Insecta*, confirming its identity as an insect, and the order *Coleoptera*, which encompasses beetles. Within this order, it belongs to the family *Tenebrionidae*, commonly known as darkling beetles. Its genus is *Tenebrio*, and its species is designated as *Tenebrio molitor*.

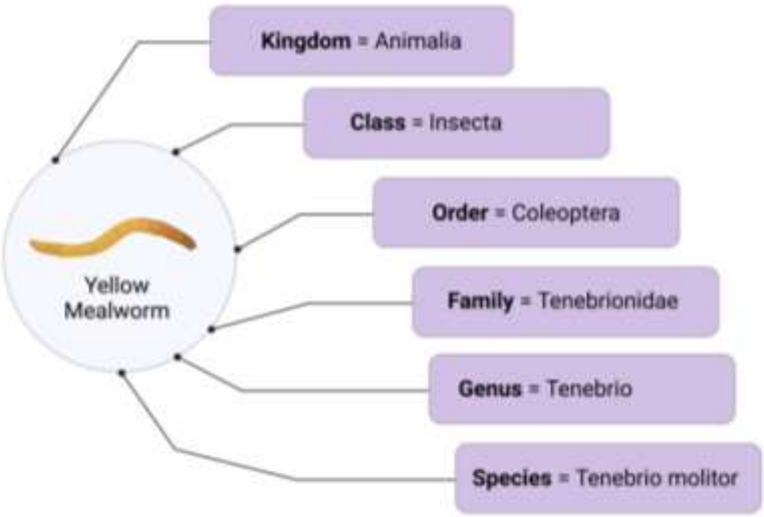

Fig. 2. Classification of mealworm [24,29]

In general, its life cycle involves four stages in which begin with egg, larva, pupa, and adult (Figure 3). According to Munoz *et al.,* [8] female beetles can lay approximately 500 eggs, which hatch within 3–9 days under optimal conditions at 25°C. The larval stage, lasting from 1 to 8 months, is identified by a light yellow-brown colour and a typical length ranging from 2.0 to 3.5 cm or more. Then, the pupal stage usually occurs over 5–28 days at a temperature of 18°C, followed by the adult stage, which lasts 2–3 months, with adults growing to about 1 cm in size. As omnivores, *T. molitor* dietary requirement involves consuming both plant and animal-based materials, such as meat and feathers, thriving on diets with approximately 20% protein.

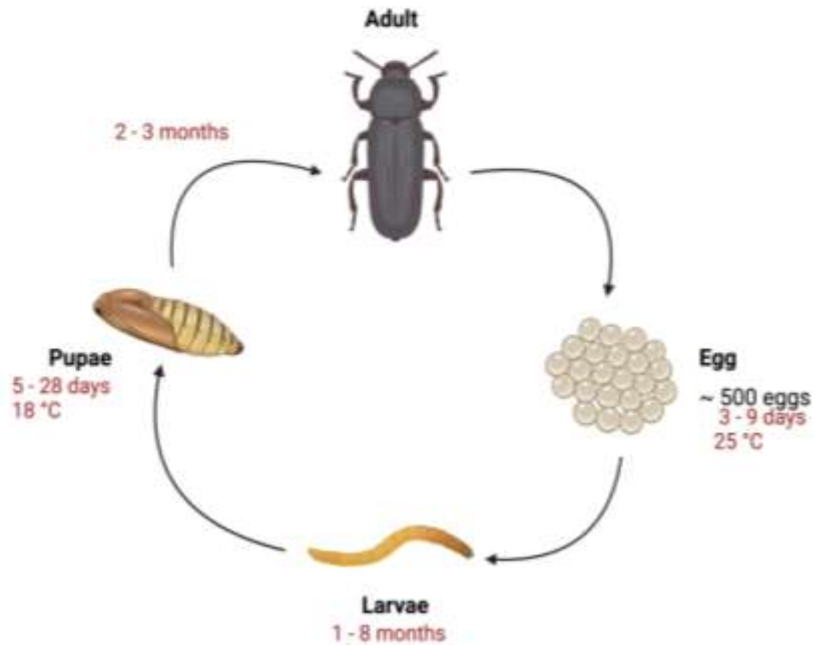

Fig. 3. Mealworm life cycle [7,29]

Commonly, the mealworm is primarily fed with cereal bran or flour (such as wheat, oats, or maize) then supplemented with fruits and vegetables for moisture, and protein sources like soybean flour, skimmed milk powder, and yeast during its cultivation [8]. The employed diet regiment to the mealworm will significantly influences its nutritional framework. Interestingly, as explained by Munoz-Seijas *et al*., [7], the mealworm in which particularly fed using cereal-based meals capable to maintain a steady constitution of crude protein, fat, and moisture. Also, diets rich in unsaturated fatty acids will modify the fatty acid composition, for instance an increase in caprylic acid concentration.

Recently, Langston *et al.,* [30], evaluated the nutritional composition of yellow mealworm larvae (*T. molitor*) reared on four different substrates. The study revealed that the crude protein content of the mealworms varied significantly, ranging from 28 to 36%, depending on the substrate, with wheat flour yielding the highest protein levels. Additionally, the micronutrients content, including essential minerals such as zinc and copper, also varied based on the substrate, indicating that substrate choice can enhance the nutritional quality of the larvae. Meanwhile, Matiolli *et al.,* [31] investigated the impact of various food waste-based diets on the lipid composition and metabolism of mealworm larvae. Their findings revealed significant variations in the larvae's chemical composition and fatty acid profiles, with oleic, palmitic, linoleic, myristic, and stearic acids constituting the major fatty acids (87.25-94.59% of total fatty acids). The study highlighted the potential of mealworm larvae as a promising nutritional resource, as their protein and mineral content can be significantly influenced by the specific substrates used during rearing. Consequently, optimizing the larval diet through careful substrate selection is crucial for maximizing their nutritional quality.

4. Nutritional Properties of Yellow Mealworm

Mealworm larvae are recognized for their substantial nutritional content, comprising approximately 50% crude protein and 30% crude fat on a dry weight basis. However, these values can fluctuate depending on the feeding substrates. For instance, the fat content can be slightly higher than protein and vice-versa [32]. In addition, mealworm equipped with a balanced amino acid profile, comprising both essential and non-essential amino acids. In terms of lipid profile, it contains several saturated fatty acids (myristic, palmitic, and stearic acids) and polyunsaturated fatty acids (oleic, linoleic, and linolenic acids) [6]. Jajić *et al.,* [33] conducted a study analyzing the fatty and amino acid composition of powdered mealworm larvae (*T. molitor*). The findings revealed a significant amount of unsaturated fatty acids, in which oleic acid (C18:1) consists of 40.83% and linoleic acid (C18:2, omega-6) accounting for 29.80% of the total fat. Additionally, significant levels of palmitic acid (16.20%) and stearic acid (2.21%) were observed. Meanwhile, the amino acid composition results shows that the mealworm sample were abundant in essential amino acids, particularly phenylalanine and tyrosine (7.7 g/100 g of protein) and tryptophan (1.8 g/100 g of protein), fulfilling the FAO/WHO/UNU criteria.

Meanwhile, Langston *et al.,* [30] comprehensively researched the nutritional profile of *T. molitor* larvae reared on four substrates: wheat bran, wheat flour, maize flour, and Lucerne pellets. The result demonstrated that the crude protein content was reported to be ranged from 28.00% (maize flour) to 36.24% (Lucerne pellets), with significant substrate-based differences ($p < 0.05$). In addition, the larvae reared on Lucerne pellets also exhibited the highest total fat content (30.84 ± 1.54%) and excellent lipid profiles, including oleic and linoleic acids. Essential minerals such as calcium (212.30 ± 10.62 mg/100 g), iron (1.27 ± 0.06 mg/100 g), and zinc (1.88 ± 0.09 mg/100 g) were identified, further emphasizing the nutritional richness of mealworms. These results illustrated the influence of dietary substrates on larval composition and highlight *T. molitor* as a nutrient-dense, sustainable food source for addressing food security issues. This comprehensive nutrient profile highlights the potential of mealworm larvae as a sustainable and nutritionally equipped food source, making them a promising candidate for addressing global food security particularly in the search of alternative protein source. The nutritional profile (proximate, amino acids, and minerals) from multiple studies from earlier research is presented in Tables 4, 5, and 6.

According to the data presented in Tables 4, 5, and 6, mealworms exhibit a promising nutritional profile compared to plant-based proteins such as soy and pea protein. Mealworms have a highly variable crude protein content (12.1–46.54%), comparable to soy (39.24%) and higher than pea protein (20.5–22.6%), making them a promising source of dietary protein. Additionally, their crude fat content (2.2–36.07%) aligns with soy (30.31%) and surpasses pea protein (2.0–3.0%), offering potential of good lipids utilization for nutraceutical products. On the other hand, the lower carbohydrate content of mealworms positions them well for low-carb dietary applications. Amino acid profile highlights mealworms superior methionine content a typically lower amino acid in many plant proteins [34]. Besides, the analysis further emphasizes mealworms' potential, with significantly higher levels of magnesium and copper compared to plant proteins. However, variability across nutritional parameters reflects inconsistencies likely influenced by rearing and processing conditions, signaling the need for standardization.

Furthermore, simply integrating the powdered mealworm into the diet is not able to provide the full nutritional benefits. That is where the extraction procedure enters the mealworm processing to acquired pure protein. Extracting protein from insects and incorporating it into food ingredients is viewed as an effective way to increase acceptance of insect consumption. In theory, insect protein extraction comprises cleaning, drying, and grinding insects into a fine powder, which is then defatted with solvents such as n-hexane (Figure 4). The protein is then solubilized in water or buffers with pH adjustment to improve extraction. Following centrifugation, the soluble protein is precipitated at its isoelectric point, washed, and dried using techniques like lyophilization or spray drying. Finally, the isolated protein is evaluated for nutritional and functional qualities [35].

Table 4
Nutritional profiles of mealworms and plant-based alternative protein sources based on previous studies

Nutritional Content	Mealworm	Mealworm	Mealworm	Mealworm	Soy	Pea
Crude protein (%)	12.1-15.5	28.57-36.24	46.54	46.07	39.24	20.5-22.6
Crude fat (%)	2.2-4.1	3.15-36.07	35.46	34.54	30.31	2.0-3.0
Ash (%)	6.2-17.8	3.15-33.74	4.88	4.04	4.61	3.2
Crude Fibre (%)	0.35-0.42	4.87-8.67	4.23	6.26	6.84	2.5
Carbohydrate (%)	65.9-79.2	NM	8.89	NM	5.08	17.0-22.0
Reference	[36]	[30]	[37]	[27]	[38]	[39]

Note: NM= Not Mentioned

Table 5
Amino acids profiles of mealworms and plant-based alternative protein sources based on previous studies

Amino acids (mg/100 mg)	Mealworm	Mealworm	Mealworm	Mealworm	Soy	Pea
Arginine	1.88-2.06	2.60-3.17	3.60	NM	4.8	5.9
Histidine	1.26-1.42	1.27-1.60	NM	ND	1.5	1.6
Isoleucine	1.02-1.30	2.13-2.51	4.12	8.38	1.9	2.3
Leucine	1.38-2.02	3.56-3.84	2.96	17.65	5.0	5.7
Lysine	1.59-1.97	2.55-4.40	2.67	0.06	3.4	4.7
Methionine	0.51-0.67	0.60-0.80	1.76	0.23	NM	NM
Phenylalanine	1.07-1.73	2.95-3.57	3.06	5.39	NM	NM
Threonine	0.81-0.95	1.90-2.77	1.47	1.75	2.3	2.5
Valine	1.11-1.44	3.00-3.65	0.65	9.74	2.2	2.7
Alanine	1.88-2.24	3.20-4.23	4.53	NM	2.8	3.2
Glycine	1.88-2.42	2.55-2.91	3.67	2.22	2.7	2.8
Glutamic acid	1.51-2.22	5.54-8.56	6.44	5.83	12.4	12.9
Proline	0.89-1.13	4.91-5.36	2.67	4.81	3.3	3.1
Tyrosine	1.08-1.56	4.33-4.91	3.86	12.30	NM	NM
Reference	[36]	[40]	[33]	[37]	[41]	[41]

Note: ND = Not Detected; NM = Not Mentioned

Table 6
Mineral profile of mealworms and plant-based alternative protein sources based on previous studies

Minerals (mg/100 g)	Mealworm	Mealworm	Mealworm	Soy	Pea
Sodium (Na)	91.72-116.98	36.4-65.0	3.0-187.0	3.0	NM
Potassium (K)	87.47-110.48	8.5-14.6	3.0-9909.0	NM	13.36
Calcium (Ca)	20.71-41.44	2.7-7.4	2.0-7276.0	300.36	1.05
Phosphorus (P)	104.46-140.64	6.5-7.8	23.0-1095.0	695.20	5.32
Magnesium (Mg)	207.96-249.67	1.9-2.3	27.0-925.0	258.24	1.62
Iron (Fe)	0.24-1.27	NM	4.56-45.19	16.4	0.06
Zinc (Zn)	1.22-2.21	1.0-1.7	0.67-15.78	2.7	0.05
Copper (Cu)	4.02-6.83	NM	0.36-2.37	NM	0.006
Manganese (Mn)	4.57-6.31	NM	1.24-30.95	NM	0.014
Reference	[30]	[40]	[42]	[41]	[43]

Note: NM = Not Mentioned

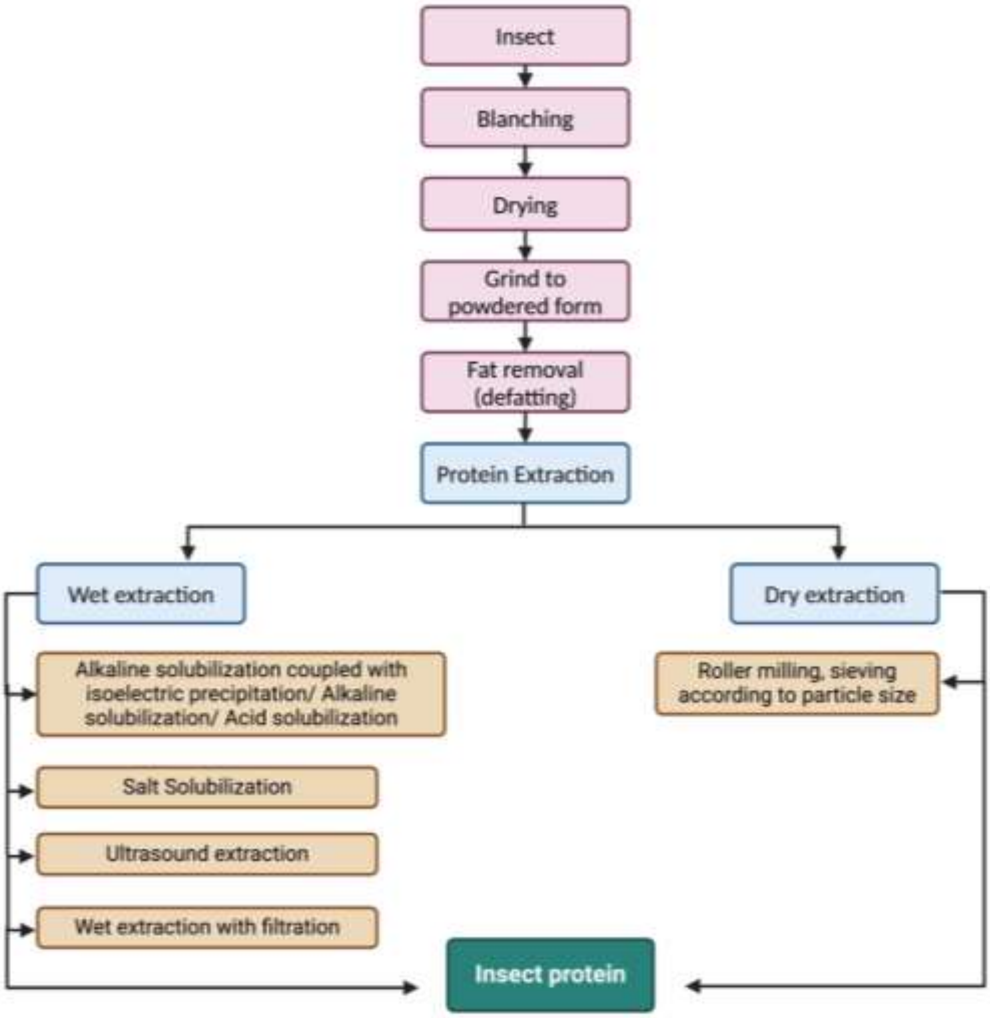

Fig. 4. General process of insect protein extraction [29,35]

Crucially, one of the important stages in the process of protein extraction from insects, is the drying, which occurs during both raw material preparation, and the protein recovery stage. In general, drying is considered as one of the ancient preservation methods that able to prolong the shelf life of food which eventually prompted its safety [44]. It effectively reduces moisture levels, which helps to retard the growth of pathogenic microorganisms and ceases most of the enzymatic reaction that can lead to spoilage. In the context of edible insects, such as mealworms, drying is particularly important as it not only enhances their microbiological stability but also safeguards their nutritional content. Thus, various drying techniques, including freeze-drying, microwave drying, oven drying and others are utilized to optimize the quality of dried insect products to guarantee the safety and suitability for both human and animal consumption [45]. Previously, Kröncke *et al.,* [32] investigated the effects of different drying methods (microwave, fluidized bed, vacuum, freeze, and rack oven drying) on the nutritional quality and lipid oxidation of *T. molitor*. The study analysed protein solubility, fat, and fibre content, alongside oxidative status by 4-hydroxy-2-nonenal (4-HNE) assay. The study revealed that the freeze-dried mealworms exhibited the highest oxidative status, while protein solubility was significantly higher in freeze and vacuum-dried samples as compared to microwave and fluidized bed drying, which showed reduced solubility ($p < 0.05$). Additionally, Vlahova-Vangelova *et al.,* [45] assessed the effects of various drying techniques which include freeze-drying, conventional drying, and microwave drying towards the quality and safety of yellow mealworm (*T. molitor*) flours. Significant differences were reported with conventional drying producing the lowest water activity (0.14) and microwave drying without freezing yielding the highest (0.54). The protein content was highest in microwave-dried flours at 45.3%, followed by freeze-dried flours at 35.2% and conventionally dried flours at 36.1%. Microwave drying resulted in increased lipid oxidation, especially in flours treated with butylated hydroxytoluene (BHT), as indicated by thiobarbituric acid reactive substances (TBARS) values of 0.45 mg MDA/kg. These results emphasize how crucial it is to choose the efficient drying techniques in order to improve the protein quality, safety, nutritional value and bioactive properties of food products made from insects, especially mealworms. Table 7 shows examples of recent successful attempts in extracting protein from mealworm by various extraction techniques.

Table 7
Recent attempt in mealworm protein extraction from previous literatures

Preparation	Extraction method	Protein recovery drying method	Yield (%)	Reference
Mealworms were ground to facilitate lipid removal. Subsequently, they were defatted with 96% ethanol at a ratio of 1:20 (w/v) at 40°C for 1 hour.	Protein extraction was facilitated using Pulsed Electric Field (PEF) technology, with varying electric field strengths (1.5, 3.125, and 5 kV/cm) and pulse numbers (200, 1100, and 2000 pulses).	Freeze-drying	9.44% to 14.55%	[46]
The larvae were pulverized and defatted	**Alkaline Extraction:** Sodium chloride (NaCl) was used for salting-in to enhance protein solubility during extraction. **Acid Precipitation:** Ammonium sulphate ($(NH_4)_2SO_4$) was applied for salting-out to effectively precipitate proteins. **Method:** Combined alkaline extraction and acid precipitation were enhanced by salting-assisted treatments.	Freeze drying	NA	[47]
• The mealworms were ground for 1 minute at 10,000 rpm using a food processor. • They were then defatted by immersing with hexane at a sample-to-solvent ratio of 1:5 (w/v).	• The defatted mealworm residue was mixed with distilled water at a ratio of 1:10 (w/v). • The pH of the suspension was adjusted to 8 using 1 M sodium hydroxide (NaOH). The mixture was stirred for 4 hours at room temperature.	Freeze drying	NA	[48]
• The mealworm larvae were defatted with n-hexane at a sample-to-solvent ratio of 1:10, stirred at 70 RPM for 48 hours at room temperature. • The samples were then centrifuged at 20,000 g for 30 minutes, and the pellets were dried under a nitrogen stream	• Protein was extracted from the defatted powder using a Phosphate-Buffered Saline (PBS) buffer (0.01 mol L^{-1} Na_2HPO_4/NaH_2PO_4 and 0.015 mol L^{-1} NaCl) adjusted to pH 7.4. • The buffer was mixed with the defatted powder at a 1:10 (w/v) ratio. • The mixture was continuously stirred at room temperature for 48 hours.	Freeze drying	41.2%	[49]

at 20°C to produce defatted powder.	• After extraction, the samples were centrifuged at 20,000 g for 30 minutes. • The supernatants were collected through vacuum filtration.			
• The larvae were exterminated by immersion in hot water for two minutes. • They were then subjected to microwave drying at 850 W for one hour until a consistent weight was achieved. • The dehydrated larvae were ground into a fine powder.	**Aqueous Extraction:** Insect flour was mixed with water (1:3), centrifuged at 5000 rpm for 10 minutes at 4°C. **Alkaline pH Extraction:** The mixture was adjusted to pH 10 using 1N NaOH, stirred under heat, and centrifuged at 5000 rpm. **pH Shift Extraction:** Defatted flour (1:15 with 0.25M NaOH) was stirred at 40°C, centrifuged, adjusted to pH 4.5, washed, and centrifuged at 5000 rpm for 20 minutes at 4°C, followed by multiple centrifugation steps at 4200 rpm.	Freeze drying	**Aqueous extraction** - 5.90% **Alkaline pH extraction** 5.63 to 14.04% **pH shift method** - 38.83%	[50]
Mealworms were fasted for two days, then frozen and freeze-dried before grinding.	• Treated insect flour with 0.2% NaOH (1:10 w/v) at pH 11 for 1 hour. • Centrifuged at 8,000 g. • Adjusted pH to 4.5 to precipitate proteins. • Centrifuged at 4°C for 20 minutes. • Washed precipitated proteins with distilled water.	Freeze-drying	NA	[51]

Note: NA= Not Available

Nowadays, researchers are actively researching in terms of increasing the quality of insect protein extraction by integrating various technologies from the solvent usage, mechanical improvement, and others to enhance the yield, physicochemical and functional properties of insect-derived protein. Recently, Perez *et al.,* [46] studied the effects of pulsed electric fields (PEF) on the extraction of proteins from yellow mealworm (*T. molitor*) and to evaluate its functional properties. The study revealed that by employing the PEF during the extraction process able to increase the percentage of protein recovery. Furthermore, they noted that the exact electric field strength of 3.125 kV/cm and 1100 pulses were capable in disrupting the β-sheet structures in which prompting the enhancement of mealworm protein functional properties. Hence, making them compatible to be incorporated in food matrices. On the other hand, looking at the solvent or chemical utilization during the protein extraction, a study by Pasini *et al.,* [49] was utilising (Phosphate-buffer Saline) PBS buffer during the protein extraction from house crickets (*Acheta domesticus*) and yellow mealworms (*T. molitor*). Theoretically, due to its neutral pH (7.4) condition, it is considered ideal for preserving the protein stability, preventing denaturation during the extraction process. Furthermore, PBS is able to securely solubilizes a diverse array of proteins that will result in higher protein yield [52]. The study revealed that the yields for cricket powder (64.3%) were significantly higher than those of mealworm powder (41.2%)[49]. The author proposed that the PBS buffer was more effective in solubilizing proteins from the cricket source.

The extraction method is essential for optimizing the potential of mealworm protein for integration into food matrices. Effective extraction techniques can improve the protein digestibility through the elimination of antinutritional compounds, such as chitin, that may interfere with the absorption. Improved digestibility ensures the complete utilization of the mealworm protein, rendering it to be “gastronomy-ready” or “food-ready” for incorporation into diverse food products such as baked goods, pasta, and meat alternatives. Hence, efficient protein extraction can significantly increase consumer acceptance of insect-based foods.

5. Perception of Edible Insects as an Alternative Source of Protein

The perception of edible insects as a viable protein source is a vital factor affecting their acceptability and incorporation into conventional diets. Insects has proven to be practical, sustainable and nutrient-dense protein source in addressing global issues such as food security, environmental sustainability. Nevertheless, without effective perception management, this effort will fail to deliver positive outcomes. Commonly, consumer perceptions of insect consumption differ significantly across regions and are usually influenced by cultural norms, individual beliefs, and psychological factors, including aversion and neophobia.

In Western nations, insects are frequently regarded as undesirable due to cultural prejudices, whereas in areas with a robust heritage of entomophagy, such as certain regions of Asia, Africa, and Latin America, they are more readily embraced [4,21]. Recent studies emphasize the importance of overcoming acceptance barriers by tackling the sensory characteristics and promoting processed insect-based products. They also stress the significance in increasing consumer knowledge regarding superior nutritional profile and environmental benefits of edible insects [3]. Table 8 shows the overview of past studies regarding the consumer perception on insect-based food products.

Table 8
Overview of previous studies on consumer perceptions of insect-based food

Main objectives	Study Region	Main Findings	Reference
To explore consumer acceptance and factors influencing the willingness to consume edible insects as an alternative protein source.	New Zealand and United Kingdom	• Consumer acceptance of edible insects was low, particularly in Western countries. • Key factors that influenced purchase intentions included trust, perceived naturalness, and innovation-adoption characteristics (IACs). • Effective communication and marketing strategies were deemed essential to improve acceptance of insect-based foods.	[53]
To assess local perceptions of edible insect consumption in Benin and identify factors influencing their adoption, focusing on socio-economic and cultural elements affecting acceptance and willingness to include insects in diets.	Benin, West Africa	• Insect consumption was more accepted in semi-arid zones (33.56%) than in humid zones (23.11%). • Acceptance was higher in rural areas (34.22%) compared to peri-urban areas (27.11%). • Perceptions were influenced by gender, age, and location. • Positive views were driven by nutritional value, taste, and safety. • Negative perceptions focused on concerns about potential toxicity.	[54]
To evaluate public perception and acceptance of edible insects in Slovenia, examining factors shaping consumer attitudes toward incorporating insects	Slovenia	• Moderate interest in insect consumption was observed among Slovenes. • Processed forms, such as insect flour, were more accepted than whole insects.	[55]

into diets and their potential as a sustainable protein source.		• Attitudes were influenced by age, gender, and education, with younger individuals and men being more receptive. • Price sensitivity played a significant role, as many respondents were willing to purchase insect products if competitively priced with conventional foods.	
To examines whether the lifestyles of young Polish consumers (Generation Z) influence their preferences for attributes of foods containing edible insects and assesses their willingness to consume these innovative products.	Poland	• Generation Z's acceptance of edible insects was influenced by pleasure orientation, health consciousness, and less attachment to culinary traditions. • Men prioritized taste and convenience, while women focused on nutritional value and appearance. • Lifestyle factors significantly influenced the willingness to consume insect-based foods.	[56]
To investigate the potential of entomophagy, or the consumption of edible insects, as a sustainable approach to improving food security and nutrition in Kenya.	Kenya	• Some edible insects were culturally acceptable in rural Kenya, but urban residents often held negative attitudes. • Highlighted the importance of raising awareness about insect consumption. • Emphasized the need for legislative frameworks to support insect farming. • Stressed the value of investing in research to promote entomophagy as a viable food source.	[57]
To investigate how entomophagy (insect consumption) aligns with Islamic dietary laws and to evaluate the acceptance of edible insects among Muslim communities, taking into account nutritional, environmental, and cultural influences.	**Regions with substantial Muslim populations** Africa, Asia, and the Middle East, where there is a historical practice of entomophagy.	• Edible insects were recognized as sustainable and nutritious, but acceptance varied among 4 Sunni Islamic school of thoughts. • Cultural norms, personal beliefs, and Halal considerations influenced perceptions. • Educating communities about the benefits was crucial for improving acceptance and promote the development of policy or standard in halal certification initiatives.	[21]
To explore consumers' motivations to accept or reject whole and processed mealworms (*Tenebrio molitor*) in their diets across five different countries, focusing on understanding the factors that influence these attitudes.	• Belgium • China • Italy • Mexico • United States America	• **Belgium**: Consumers showed moderate acceptance, driven by health benefits, but raised concerns about taste and the visibility of insects in food. • **China**: Chinese consumers displayed high acceptance of mealworms, motivated by health benefits and cultural familiarity with insect consumption. • **Italy**: Italian consumers demonstrated strong aversion, placing less importance on health benefits and exhibiting a significant "yuck factor." • **Mexico**: Mexican consumers, with a tradition of insect consumption, were more accepting of mealworms due to health	[9]

		benefits and cultural practices, though some aversion persisted. • **United States**: U.S. consumers had mixed responses, with health benefits encouraging acceptance but psychological barriers like aversion and unfamiliarity limiting it.	
The study examines why innovative student chefs are willing or unwilling to use mealworms as a new ingredient, aiming to identify factors that increase chef acceptance and promote consumer adoption in the restaurant industry.	Quebec, Canada	• Prior consumption of insects lowered barriers such as neophobia and disgust. • Chefs showed interest in using insect-based ingredients but faced challenges with social acceptability, preparation complexity, high costs, and limited availability. • Highlighted the importance of education and exposure to overcome acceptance barriers and promote insect incorporation in cuisine.	[58]
To investigates the barriers and benefits of insect consumption, focusing on the impact of disgust, social influence, and moral concerns on individuals' willingness to try insect-based products.	United Kingdom	• Disgust and moral concerns were identified as major barriers to insect consumption. • The study emphasized the need for further research to overcome these challenges. • Highlighted the role of social influence in shifting attitudes toward eating insects.	[59]
To explore the attitudes of Italian consumers towards entomophagy.	Italy	• Curiosity and environmental benefits were key factors influencing Italians' willingness to eat insects. • Clear communication about insect species and their culinary uses was crucial for increasing acceptance. • The study emphasized consumer traits and product features necessary to overcome psychological resistance to entomophagy.	[60]
To examines the potential for developing an edible insect food industry in Latin America, focusing on the key challenges and opportunities within the sector through a systemic competitiveness approach.	**Latin America** Mexico, Brazil, Colombia, Venezuela, Ecuador, and Peru	• Consumer acceptance of edible insects was low in urban areas due to cultural biases, despite strong entomophagy traditions in some regions. • The study emphasized the importance of national and regional strategies to promote the edible insect industry. • Highlighted the need for innovation rooted in traditional practices and active stakeholder engagement to improve competitiveness and sustainability.	[61]
To investigate the factors influencing the willingness to eat (WTE) insect-containing foods in Western cultures, particularly focusing on the role of social norms and the emotional response of disgust.	Denmark	• Social norms strongly influenced insect-tasting behaviour, encouraging individuals to try insect-based foods despite common feelings of disgust. • Traditional cultural practices and personal preferences also shaped attitudes toward entomophagy.	[4]

To explore how young consumers in Italy accept and appreciate insect-based snacks, specifically examining the sensory qualities and factors that influence their liking of these products.	Italy	• Young Italian consumers showed growing interest and willingness to try insect-based foods, but cultural barriers hindered full acceptance. • Taste was a significant factor in acceptance, and overcoming initial disgust was crucial for positive feedback on insect-based products. • While young consumers were open to trying these snacks, they were not yet ready to incorporate them regularly into their diets.	[62]
To explores the acceptance of insect-based foods in Germany, focusing on factors influencing willingness to consume products like insect burgers and buffalo worms. It examines variables such as food disgust, prior insect consumption, food neophobia, gender, sensation seeking, and sustainability awareness.	Germany	• Food disgust and prior insect consumption were major factors influencing willingness to eat insects. • Additional factors included food neophobia, gender, sensation seeking, and food technology neophobia. • The study recommended marketing strategies that reduce disgust and emphasize positive taste experiences instead of solely focusing on sustainability.	[63]

Based on the information from Table 8, it highlights recurring themes that focuses into cultural, social, economic, and psychological domains. These are the factors that suggests able to influence consumer acceptance and consumption of edible insects. Cultural biases and psychological barriers, including food neophobia and disgust sensitivity, are the consistent barriers of edible insects consumption. For example, Sosa *et al.,* [9] found that Italian consumers were significantly less willing to consume whole insects compared to processed products, with the "yuck factor" being a critical deterrent ($p < 0.05$). Similarly, Tuccillo *et al.,* [60] reported that Italian participants preferred less obvious insect products like crackers, which scored above 4 on a 7-point scale, compared to whole crickets, which scored below 4. In contrast, regions with a strong tradition of entomophagy, such as China and Mexico, showed higher acceptance, as cultural familiarity mitigated psychological barriers [9]. Serrano [61] corroborated these findings by noting higher acceptance rates in rural Latin American areas with entomophagy heritage compared to urbanized regions. These studies suggest that promoting processed insect products and leveraging cultural familiarity can effectively enhance acceptance.

Furthermore, perceptions regarding edible insects are significantly shaped by societal norms. Jensen and Lieberoth [4] demonstrated that social contexts significantly influenced willingness to consumed roasted mealworms, with 81% of Danish participants trying them despite initial aversion ($p < 0.05$). This demonstrates how perceived social norms are capable to overcome individual psychological barriers. Similarly, Russell and Knott [59] suggested that social influence could reduce disgust and improve acceptability, albeit with context-dependent effects. These findings highlight how crucial it is to leverage social influence through targeted marketing and community-based initiatives to normalize edible insect consumption.

Consumer behaviour is further influenced by economic considerations such as availability and pricing. According to Wang *et al.,* [53], perceived complexity and trust had a substantial impact on purchase intentions. Complexity hindered acceptance, however, trust positively correlated with it ($p < 0.05$). It was suggested that if insect products were priced similarly to conventional proteins, consumers will be more inclined to consider consuming them. This is consistent with Poulin *et al.,*

[58], who demonstrated that although student chefs were enthusiastic about employing insect-based foods, high costs and restricted availability were major obstacles in the culinary setting. In a similar condition, Slovenian customers favoured processed insect products and were more inclined to accept them if they were offered at competitive price [55].

In short, consumers overwhelmingly prefer processed insect products over whole insects while cultural familiarity and social norms are vital in reducing disgust and neophobia. Also, significant barriers persist in the form of high costs and limited availability. In order to successfully integrating edible insects into diets and advancing sustainable food systems requires a strategy that combines cultural sensitivity, social influence, and economic accessibility.

As acceptability increases, boost by improved sensory attributes, enhanced nutritional profiles, and effective education campaigns, the demand for insect-based products able to grow organically. This increasing demand will prompt greater innovation, encouraging the integration of insect proteins, such as mealworm protein, into various food matrices. This can be achieved through a strategic approach in addressing perception barriers and aligning product development with consumer expectations. This approach creates a wide spectrum of possibilities for exploring the incorporation of mealworm protein into diverse food matrices.

6. Food application of mealworm protein

The integration of insect protein, particularly protein derived from *T. molitor,* represents a promising advancement in developing sustainable and nutritionally enriched food products. Renowned for its high protein content, comprehensive amino acid profile and versatility, mealworm protein is gastronomy-ready for incorporation into various food matrices, including baked goods, pasta, snacks, and meat alternatives. As consumer interest in alternative proteins grows, mealworm protein offers a practical solution to meet nutritional needs while addressing pressing environmental issues [8]. Table 9 depicts previous successful attempt in incorporating mealworm protein into several food products.

As can be seen in Table 9, other than improving the food properties by incorporation of mealworm protein in the food, it also shows the possibility of exerting the health benefits from consumption those products. For instance, the study by Pasini et *al.,* [49] revealed that adding protein-rich powders from yellow mealworms (*T. molitor*) to pasta significantly improves its nutritional profile while preserving acceptable culinary qualities. This is due to by swapping 14% of durum wheat semolina with mealworm protein increases the pasta's protein content, prompting in solving dietary protein deficiencies, particularly in carbohydrate-heavy diets. The study suggested that the enriched pasta capable in improving the firmness and water absorption, amplifying its texture and overall acceptance, which is suitable for health-conscious type of consumer. Tang *et al.,* [64] illustrated the benefits of integrating mealworm powder into protein shakes, highlighting its capacity to improve nutritional quality and customer acceptance, especially when marketed alongside sustainability narratives. They reported that mealworms offer a significant increment of protein and micronutrients while adeptly concealing undesirable flavours linked to conventional protein powders. Mealworm protein is positioned as a favourable choice for people with active lifestyles who desire convenient, nutritious recovery options that correspond with their health and sustainability principles.

Table 9
Overview of successful applications of mealworm protein in various food products

Food product/ matrix	Percentage of mealworm protein (%)	Nutritional profile	Physicochemical/sensory properties	Reference
Sponge cake	10 -20%	• **Increased Protein**: Sponge cakes made with mealworm flour had higher protein content. • **Amino Acids**: Mealworm flour contributed more essential amino acids compared to wheat flour, enhancing nutritional value. • **Proximate Composition**: Mealworm flour increased levels of lipids, ash, and dietary fibre, boosting overall nutrition.	• **Texture**: Reduced sponge cake hardness and brittleness. • **Colour**: Altered colour parameters by decreasing lightness and increasing redness and yellowness.	[3]
Biscuits	10 – 20%	• Biscuits with 15 % mealworm powder had higher protein, fat, fibre, and essential amino acids. • Carbohydrates and 5-HMF content were reduced in mealworm biscuits. • Essential amino acids were significantly higher compared to 100 % white wheat flour biscuits.	• Mealworm powder weakened the gluten network, creating a less dense and viscous biscuit structure. • Improved protein digestibility due to easier access for digestive enzymes. • Lower glycaemic index (GI) observed in mealworm biscuits. • Reduced rapidly digestible starch and increased slowly digestible starch.	[65]
Bread	10%	• Yellow mealworm powder increased protein, lipids, and fibre in bread. • Essential amino acids, including valine and tyrosine, were significantly higher in insect bread compared to white flour bread.	• Mealworm powder reduced bread specific volumes due to gluten network dilution. • No significant differences in specific volumes between white flour and mealworm protein-enriched breads. • Fatty acid profile of mealworm protein-enriched bread was dominated by polyunsaturated fatty acids.	[37]
Cake	0 – 5%	• Mealworm powder significantly increased cake protein content. • Protein levels by mealworm addition: 0 % powder = 5.99% 5 % powder = 8.67% 10 % powder = 11.12%	• **Texture** Increased firmness and reduced springiness, resulting in a denser cake in mealworm powder enriched cake. • **Moisture Content**: The cake mixed with the mealworm powder showed a minor decrease in initial moisture content because of the addition of the dry components.	[66]

			• **Colour** Significant colour changes (ΔE) observed, especially at higher mealworm powder levels, due to its dark-brown colour.	
Pasta	14%	NA	• **Colour** Mealworm-enriched pasta had a darker colour (L* = 59.9) compared to control pasta (L* = 76.7). • **Texture** Firmness increased with mealworm protein (13.8 N) compared to control pasta (12.4 N). • **Water Absorption** Higher water absorption in mealworm pasta (178 %) compared to control pasta (150 %), enhancing moisture retention during cooking.	[49]
Tofu	Mealworm protein was incorporated into tofu at a 1:1 ratio with soybean flour (50% each).	NA	• **Rheological Properties** Mealworm protein isolate improved tofu gel formation and structural integrity. • **Texture** Enhanced overall texture compared to traditional soybean-only tofu.	[67]
Protein shake	3%, 6%, 9%, 12%, and 15%.	NA	• Mealworm protein enhanced sensory acceptability by masking undesirable flavours. • Its powdered form reduced negative reactions to the visual appearance of insects.	[64]
Chicken surimi	0 – 70% of mealworm protein isolate (MPI)	NA	• **Texture** Mealworm protein reduced hardness and increased tenderness, making chicken surimi more suitable for elderly consumers. • **Water-Holding Capacity (WHC)** Enhanced WHC improved moisture retention and juiciness while reducing cooking loss. • **Viscoelastic Properties** Decreased storage modulus (G') with higher mealworm protein content indicated a softer gel structure. • **Protein Interaction** Mealworm protein strengthened the protein	[68]

network, improving extrudability for 3D printing and enhancing product stability.

Note: NA= Not Available

The successful incorporation of mealworm protein has been proven effective in boosting the protein content of baked goods and pasta while enhancing the functional properties of snacks and meat substitutes. However, the continued success of these applications relies on addressing key challenges, such as optimizing extraction methods and improving consumer acceptance of insect-based foods. With the growing demand for alternative proteins, mealworm protein is poised to play a vital role in addressing global food security issues.

7. Future perspective

One of the future directions of the mealworm protein is the production of insect-based hydrolysates that contains bioactive peptides, that serves as the alternative remedies for both hypertension and diabetic patients. In general, insect-based protein hydrolysates have several bioactive advantages, such as antioxidant, anti-obesity (antidiabetic), and liver-protective (hepatoprotective) properties [69]. Rivero-Pino *et al.,* [70] studied the effects of ultrasound pretreatment and sequential hydrolysis with subtilisin and trypsin on producing α-glucosidase inhibitory peptides from *T. molitor*. The study revealed that temporary ultrasound able to improve the release of the bioactive peptide. It was suggested that the employment of specific protocol of ultrasound during hydrolysates production able to result in high-bioactive peptide. In fact, the peptide produced shown a potential to be incorporated food that are tailor-made for low glycaemic index product. Recently, Muñoz-Seijas *et al.,* [7] aimed to investigate the how variation of pre-treatments and extraction methods impacted the antioxidant activity and the efficiency of the mealworm protein hydrolysates extraction. They found out that by integrating the microwave-assisted extraction (MAE), the recovery of phenolic compounds and antioxidant activity of the compound are both significantly increased. The author also highlighted that the enzymatic hydrolysis effectively increased protein hydrolysis and free amino acid content. These findings demonstrates that the optimization of extraction techniques is vital in the effort of enhancing the nutritional and functional properties of edible insects by product such as hydrolysates.

Interestingly, beyond enhancing the nutritional and bioactive properties of food, mealworm protein can also play a critical role in texture manipulation and rheology. Its exceptional emulsifying and gelling abilities make it a versatile ingredient in food innovation, with exciting applications such as 3D food printing. Chao *et al.,* [68] successfully incorporated mealworm protein isolate (MPI) into chicken surimi using coaxial 3D printing to create texture-modified food for the elderly. The addition of 50 % MPI revealed to significantly improved water-holding capacity and reduced surimi hardness, meeting elderly dietary guidelines. This innovative approach enhances the sensory and nutritional quality of food for individuals with swallowing difficulties and highlights the potential for further research into sensory improvements and softening agents.

Fascinatingly, the practice of mealworm rearing also seamlessly aligns with future innovations, offering the unique environments in which the farming of mealworm can coexist with diverse activities. Vesterlund *et al.,* [71] evaluated the feasibility of using excess heat from data centres for sustainable mealworm farming. The results revealed that mealworms able to reach full larvae size in approximately 8 weeks at 30°C with the excess heat from the data centres, which involved a strict schedule of feeding, and added water, compared to 14 weeks in a control group at 20°C. Additionally, the study highlighted that simply by increasing the temperature without adequate feed and water did not enhance growth rates. The research concluded that utilizing data centre excess heat for mealworm farming presents a viable method for improving local protein production while promoting energy sustainability.

8. Conclusion

This review concluded that *Tenebrio molitor* (yellow mealworm) has the potential to become one of the key players inside the global market that focuses on alternative protein and functional food. Its exceptional nutritional composition prompting mealworm to be a versatile ingredient for a wide range of food applications. Moreover, the adaptability of mealworm farming to sustainable practices, such as utilizing food by-products and integrating circular economy (CE) principles, further enhances its appeal as an environmentally friendly protein source. In fact, mealworm protein capable of competing with traditional animal and plant-based protein. Hence, innovations in extraction methods, such as enzymatic hydrolysis and microwave-assisted techniques, have significantly improved its functionality, bioavailability. These advancements have positioned mealworm to be “gastronomy-ready” and “food-ready” as demonstrated by its applications in food matrices such as baked goods, pasta, snacks, and meat substitutes. More importantly, the advancements in 3D printing technologies and texture modification highlights mealworm protein’s capacity to cater to specialized dietary needs, such as those for elderly individuals or patients with dysphagia. However, challenges remain in the effort of improving consumer acceptance and overcoming cultural biases toward insect-based foods. Strategic marketing efforts, consumer education, and the development of processed forms that mask the visual aspects of insects are critical to warrant a widespread adoption. Thus, ongoing developments in protein extraction, sensory profiling, acceptability studies, and bioactive peptides research are paving the blueprint for yellow mealworm to champion as a sustainable and nutrient rich alternative protein. These initiatives will position mealworm protein as a novel solution to meet the evolving demands of the future modern food industry.

Conflict of interest

The authors declare no conflict of interests.

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