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Nutritional value and advances of mealworm (*Tenebrio molitor*) as a sustainable functional ingredient in bakery products: A key step toward sustainable diets

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ABSTRACT

Bakery products are most popular and widely accepted carrier of energy and nutrient in the human daily diet. However, their nutritional quality poses many challenges to achieving balanced diet. Reformulating bakery products to make them healthier could therefore have significant benefits. In recent year, mealworm (MW), *Tenebrio molitor*, one of the approved edible insects, has gained much attention as promising sustainable functional ingredient, since its high nutritional value and environmental benefits. Therefore, incorporation of MW into bakery products confers interesting opportunities to reformulate bakery products, making them more affordable, sustainable, and healthier. This review aims to provide overview of the nutritional value of MW and conclude current advances in its potential as a functional ingredient in bakery product development. MW is rich source of protein (29.20 % - 64.34 %, w/w), oil (14.875 – 39.60 %, w/w), and minerals, and has been used as wheat flour substitution in various bakery products. Additionally, its incorporation in bakery products improve their nutritional quality, but alter the physical and sensory properties of the final products. Overall, spreading in-depth knowledge can guide further studies on the reformulation of bakery products with MW, thereby meeting with consumers' expectations and further reducing the distance between the consumers and products.

1. Introduction

Bakery products are attractive and widely accepted foods in the daily diet and are considered a significant source of energy and nutrients in daily diets (Dong and Karboune, 2021; Lin, 2022). These products are highly varied, such as bread, cookies, biscuits, muffins, and cakes, and their market size is steadily increasing (Tarahi et al., 2024). The global bakery product market size is valued at 475.22 USD in 2024 and is expected to reach 809.72 billion USD by 2033 (Straits Research, 2024). However, the above products usually use refined flour to produce products with better sensory, which adversely results in a large loss of nutrients (Gökçe et al., 2023; Mihaly Cozmuta et al., 2022; Zhang and Li, 2024). With the increasing awareness of health and sustainability, consumers are moving towards for healthier and sustainable bakery products (Guiné and Florença, 2024; Zhang et al., 2023). This demand has prompted the bakery industry to focus on developing novel sustainable bakery products with additional health benefits (Abedinia et al., 2025; Di Cairano et al., 2022). From the technological viewpoint, modifying bakery product formulations is a feasible and promising strategy to increase nutritional value and deliver health benefits (Abedinia et al., 2021; Mitelut et al., 2021; Tarahi et al., 2024). To this end, the bakery industry is continuously exploring novel high-nutrient ingredients from sustainable sources and introducing them into formulations to achieve healthier and more sustainable bakery products (İncili et al., 2025; Tsykhanovska et al., 2024).

Mealworm (MW, Fig. 1), *Tenebrio molitor*, is one of the approved edible insects in many countries and has received much attention as a novel food source, since its rich in nutritional value, such as protein, oil, minerals, and bioactive compounds (Gumul et al., 2023; Kępińska-Pacelik et al., 2023; Mattioli et al., 2024; Son et al., 2020). Compared to

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traditional livestock, MW can be reared on low-cost side streams and/or wastes as feed and requires for space, water, and maintenance, which has high environmental benefits (Langston et al., 2024; Montalbán et al., 2022). Currently, the European Commission has approved MW as a novel food to be used in a variety of food products (e.g. bread and cakes) and authorised its placement on the European Union market (European Commission, 2025). Therefore, Incorporating MW into bakery products presents a valuable opportunity to reformulate bakery products to meet growing consumer demand for healthier and more sustainable food products. On the other hand, the increasing world population and corresponding increase in the demand for food has placed heavy burden on natural environment and exacerbated global food insecurity (Abedinia et al., 2020; Amiri et al., 2025; Lampová et al., 2024; Molotoks et al., 2021). Edible insects are significantly considered as novel and sustainable nutrition source to address global food insecurity (Gantner et al., 2022; Kowalski et al., 2022). Including insects in our daily diet can contribute to assure food security, provide affordable and nutritious foods for everyone, and is a key to achieving more sustainable food system and diets, which also in line with sustainable development goals (SDG) (Delgado et al., 2023; Lange and Nakamura, 2021). Meanwhile, this dietary shift also offers a promising opportunity for win-win outcomes for human and nature.

Therefore, this review provides overview of the potential nutritional value of MW to deepen the understanding of its potential as a sustainable nutritional ingredient. Additionally, this review concludes the most recent advances in the use of MW as functional ingredient in bakery product formulations. This review focuses on the last research papers published in the past five years (from 2021 to 2025) on the nutritional value and bakery product applications of MW. Spreading in-depth knowledge can guide further studies on the reformulation of bakery products with MW, thereby meeting with consumers' expectations and further reducing the distance between the consumers and products.

2. Nutritional value of MW

MW is rich in valuable nutritional values, such as oil, protein, fibre, minerals, and phenolics, making it a particularly promising and sustainable food ingredient in food applications. Table 1 summarises the nutritional composition of MW, which varies with species, rearing conditions (e.g. feed and temperature), age, and development stages (Cantero-Bahillo et al., 2025; Kopecká et al., 2024; Langston et al., 2024; Toviho and Bársony, 2022).

2.1. Oil

MW is rich a source of oil, ranging from 14.87 % to 39.60 %, w/w. The oil content of MW is not below some commercial edible oil sources, such as sunflower (35.33 % - 59.67 %, w/w), rapeseed (32.28 % - 38.80 %, w/w), and olive (12.25 % - 33.80 %, w/w), indicating that MW is a promising source of oil (Gagour et al., 2024; Hosni et al., 2022; Stojanović et al., 2023). In terms of fatty acid profile (Table 2), MW oil is rich in monounsaturated fatty acids (MUFA, 27.54 % - 54.41 %) and polyunsaturated fatty acids (PUFA, 22.35 % - 45.76 %), mainly comprised of oleic acid (C18:1, 27.06 % - 50.25 %) and linoleic acid (C18:2; 22.23 % - 43.80 %). Regarding saturated fatty acids (SFA; 22.17 % - 29.18 %), palmitic acid (C16:0) is most abundant, ranging from 15.78 % - 22.73 %. The fatty acid composition of MW oil is similar to that of plant oils, such as sunflower oil, soybean oil, corn oil, and rice bran oil (Cherif and Slama, 2022; Xu et al., 2021). From nutritional point of view, oleic acid (C18:1) and linoleic acid (C18:2) have demonstrated their positive effects on prevention of cardiovascular disease (CVD) (Yang et al., 2022). The high content of oleic acid (C18:1) and linoleic acid (C18:2) in MW oil could has potential to promote health. Notably, MW oil contains palmitoleic acid (C16:1, 0.48 % - 3.62 %). Palmitoleic acid, an important and rare $\omega-7$ fatty acid, is considered to be a lipokine that has been shown to have positive preventive effects on diabetes, insulin resistance, inflammation, and metabolic syndrome (Frigolet and Gutiérrez-Aguilar, 2017; Guo et al., 2022). Nevertheless, its dietary sources are largely limited, with fish oil, macadamia nut oil, and sea buckthorn seed oil being the mainly naturally sources (Takeno et al., 2023; Zhang et al., 2024). The above indicate the MW oil fraction has potential to be as a functional dietary oil source.

Apart from the above, MW oil also contains various biological compounds, such as carotenoids, phenolics, tocopherols, and squalene. These compounds have various biological activities for human health, such as antioxidant and anti-inflammatory (Coornaert et al., 2024; Liu

Fig. 1. Mealworm (*Tenebrio molitor*).

et al., 2021). The total carotenoids content and total tocopherol content in MW are 13.65 (mg/kg of oil) and 105.8 – 195.7 (mg/kg of oil), respectively (Jeon et al., 2016; Martínez-Pineda et al., 2024; Son et al., 2020). Son et al. (2020) detected squalene (21.1 mg/kg of oil), α-tocopherol (6.3 mg/kg of oil), γ-tocopherol (123.5 mg/kg of oil), β-tocopherol (8.5 mg/kg of oil), and δ-tocopherol (6.1 mg/kg of oil) in MW oil. Furthermore, Martínez-Pineda et al. (2024) analysed the phenolic profile and tocopherols of MW oil and detected apigenin (0.94 mg/100 g of oil) and three forms of tocopherols, including α-tocopherol (55.8 mg/kg of oil), γ-tocopherol (46.8 mg/kg of oil), and δ-tocopherol (3.2 mg/kg of oil).

2.2. Protein

The protein content in MW ranges from 29.20 % to 64.34 % (w/w), which is not below that of traditional animal and plant protein sources, such as beef (20.40 % - 32.43 %, w/w), pork (20.10 % - 28.21 %, w/w), chicken (18.90 % - 27.40 %, w/w), legumes (23.79 % - 46.77 %, w/w), and cereals (8.46 % - 17.91 %, w/w) (Drewnowski et al., 2024; Xu et al., 2023; Yang et al., 2023). This suggests that MW could be considered a promising and sustainable protein source.

Amino acid composition and protein digestibility are important indicators for evaluation of protein nutritional quality (Igual et al., 2021). As shown in Table 3, MW protein contains 9 essential amino acids and 10 non-essential amino acids. Among all essential amino acids, valine, leucine, lysine are most abundant, while methionine and tryptophan are limiting amino acids. Except for tryptophan, the content of all essential amino acids in MW protein perfectly meets amino acid scoring pattern for adults recommended by Food and Agriculture Organization (FAO, 2013). Among all non-essential amino acids, aspartic acid, glutamic acid, proline, alanine, and glycine are most abundant, contributing to sweet and umami taste in MW. Regarding protein digestibility of MW, Lampová et al. (2024) used the in vitro digestible indispensable amino acid score (DIAAS) methodology to evaluate the protein quality of MW and reported that the DIAAS value of MW was 80.52 % (using conversion factor of 6.25), which can be categorised into good protein quality (value between 75 and 95). Notably, protein digestibility is influenced by processing method (Hammer et al., 2023). In another study, Hammer et al. (2023) compared the effects of different processing methods on the protein digestibility of MW, using blanching, freeze-drying, pluverising, oven-drying, and chitin reduction. The results showed that oven-drying and chitin reduction exhibited adverse effect on protein digestibility of MW. Therefore, developing appropriate processing method could further improve protein quality of MW.

2.3. Minerals

As shown in Table 4, MW can be considered a good source of dietary minerals. MW contains high amounts of macrominerals, including potassium (K, 765 – 1334.22 mg/100 g), phosphorus (P, 216.32 – 915.07 mg/100 g), magnesium (Mg, 145 – 324.36 mg/100 g), sodium (Na, 108.79 – 290 mg/100 g), and calcium (Ca, 33.63 – 225.07 mg/100 g). Notably, increasing potassium intake and decreasing sodium intake have been shown to have positive effects on CVD (Salman et al., 2024). According to the World Health Organization (WHO) recommendation, the recommended dietary intake of sodium and potassium for adults should be less than 2000 mg/day of sodium and at least 3510 mg/day of potassium (WHO, 2013). The high potassium and low sodium content of MW indicates its potential as a promising potassium dietary source into human diet to improve potassium daily intake and reduce the risk of CVD.

In terms of microminerals, zinc (Zn, 8.86 – 53.05 mg/100 g) and iron (Fe, 2.57 – 27.24 mg/100 g) are most abundant, followed by copper (Cu, 0.86 – 18.65 mg/100 g), manganese (Mn, 0.54 – 4.10 mg/100 g), and selenium (Se, 0.0474 – 0.28 mg/100 g). Hidden hunger, also known as micronutrient deficiency, affects sustained health of more than 2 billion people in the world due to low intake of some microminerals, such as zinc and iron (Das and Padhani, 2022). It suggests that incorporation of MW into food production and/or the human diet could help address hidden hunger.

Table 1
Proximate compositions (%, w/w) of mealworm (MW, *Tenebrio molitor*).

Protein	Oil	Ash	Fibre	Country	Refs.
49.89	29.64	3.65	8.54	Austria	Kowalski et al. (2022)
43.6 – 53.4	22.3 – 30.0	3.64 – 5.19	6.79 – 7.31	Poland	Bordiean et al. (2022)
43.00 – 45.23	37.80 – 39.60	3.60 – 3.65	10.90 – 12.13	Hungary	Toviho & Bársony (2022)
55.59	14.87	4.04	–	France	Karoui et al. (2025)
54.41 – 64.34	22.46 – 36.01	2.85 – 5.65	–	Czech Republic	Kopecká et al. (2024)
48.54 – 59.18	20.23 – 35.55	–	5.10 – 8.07	Lithuania	Jankauskienė, Aleknavičius, et al. (2024)
29.2 – 49.0	9.0 – 44.3	3.7 – 5.5	–	Greece	Vrontaki et al. (2024)

2.4. Phenolic compounds

Phenolic compounds, natural antioxidants, have various beneficial properties, such as antioxidant and anti-inflammatory (Sun and Shahrajabian, 2023). Recent studies report that MW contains various phenolic compounds (Anusha and Negi, 2025; Gumul et al., 2023; Rocchetti et al., 2024). In the study by Gumul et al. (2023), they detected the phenolic profile of MW using HPLC (high-performance liquid chromatography). They found 11 phenolic compounds in MW, including gallic acid (4.63 mg/100 g), vanillic acid (1.36 mg/100 g), protocatechuic aldehyde (23.19 mg/100 g), 2,5-dihydroxybenzoic acid (0.15 mg/100 g), ellagic acid (0.26 mg/100 g), caffeic acid (0.06 mg/100 g), ferulic acid (0.54 mg/100 g), *p*-coumaric acid (0.06 mg/100 g), sinapic acid (0.15 mg/100 g), quercetin 3-O-glucoside (0.40 mg/100 g), and rutin (0.40 mg/100 g). In another study, Rocchetti et al. (2024)

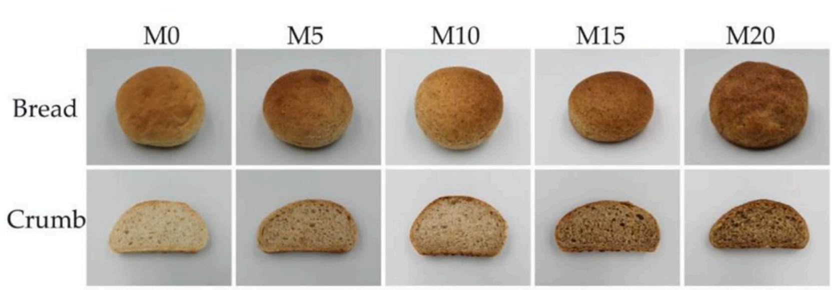

Fig. 2. Appearance of bread enriched with mealworm powder: M0 – 100 % wheat flour bread; M5 to M20 – bread with 5 % to 20 % of wheat flour replaced by mealworm powder (Xie et al., 2022).

Table 2
Fatty acid profile of mealworm (MW).

Fatty acid (%)	Noyens et al. (2023)	Cantero-Bahillo et al. (2025)	(Nam et al., 2025)	Mattioli et al. (2024)
Lauric acid (C12:0)	–	0.34 – 0.52	0.34 – 0.39	0.24
Tridecanoic acid (C13:0)	–	0.05 – 0.07	0.08	–
Myristic acid (C14:0)	1.65 – 2.95	4.20 – 4.65	3.95 – 4.03	3.73
Pentadecanoic acid (C15:0)	0.13 – 0.25	0.06 – 0.10	0.16	–
Palmitic acid (C16:0)	17.96 – 22.73	15.78 – 17.06	18.06 – 18.21	18.79
Margaric acid (C17:0)	0.10 – 0.26	0.12 – 0.19	0.18 – 0.19	–
Stearic acid (C18:0)	2.25 – 2.87	2.13 – 2.38	2.64 – 3.08	5.77
Arachidic acid (C20:0)	0.08 – 0.12	–	0.12	0.27
SFA	22.17 – 29.18	22.68 – 24.97	25.53 – 26.26	28.80
Myristoleic acid (C14:1)	–	0.37 – 0.40	0.02	0.13
Palmitoleic acid (C16:1)	0.48 – 1.34	3.35 – 3.62	1.61 – 1.94	1.80
Heptadecenoic acid (C17:1)	–	0.09 – 0.14	0.15 – 0.16	–
Oleic acid (C18:1)	27.06 – 43.19	43.45 – 50.25	42.11 – 42.58	38.41
Eicosenoic acid (C20:1)	–	–	0.16	0.28
MUFA	27.54 – 44.53	47.26 – 54.41	44.05 – 44.86	40.62
Hexadecadienoic acid (C16:2)	0.20 – 0.34	0.12 – 0.19	–	–
Linoleic acid (C18:2)	26.29 – 43.80	22.23 – 27.32	27.61 – 27.99	28.06
Linolenic acid (C18:3)	0.76 – 1.62	nd	1.15 – 1.35	0.90
PUFA	27.25 – 45.76	22.35 – 27.51	28.76 – 29.34	28.96
Extraction method	Soxhlet extraction	Solvent extraction	Supercritical fluid and ultrasound-assisted extraction	Soxhlet extraction
Origin	Belgium	Spain	South Korea	Italy

SFA – saturated fatty acids; MUFA – monounsaturated fatty acids; PUFA – polyunsaturated fatty acids.

Table 3
Amino acid (g/100 g of protein) profile of mealworm (MW).

Essential amino acids (EAA)	Oh et al. (2024)	Berthelot et al. (2024)	Kröncke & Benning (2023)	Bogusz et al. (2024)	FAO (2013)
Histidine	4.25 – 7.03	2.82 – 6.07	1.1 – 2.0	4.29 – 4.54	1.5
Threonine	3.15 – 6.43	1.17 – 4.46	1.2 – 6.4	3.87 – 4.24	2.3
Valine	2.53 – 7.77	4.25 – 4.99	2.2 – 3.8	5.29 – 5.87	3.9
Methionine	0.72 – 3.91	0.84 – 1.26	–	0.47 – 0.58	
Lysine	5.47 – 13.11	3.86 – 4.84	1.2 – 3.7	5.43 – 6.07	4.5
Isoleucine	2.21 – 4.92	2.54 – 3.33	1.6 – 3.3	3.66 – 3.99	3.0
Phenylalanine	1.87- 4.69	1.19 – 3.90	1.2 – 8.2	3.54 – 4.16	
Leucine	2.94 – 8.20	2.45 – 7.99	2.2 – 10.9	6.44 – 7.51	5.9
Tryptophan	–	1.62 – 2.07	–	–	6.0
Total EAA	23.14 – 56.06	20.74 – 38.91	10.7 – 38.3	32.99 – 36.96	
Non-essential amino acids (NEAA)					
Aspartic acid	6.38 – 20.34	1.95 – 13.00	0.5 – 4.3	–	–
Arginine	3.92 – 8.18	4.23 – 9.28	1.9 – 3.9	4.99 – 5.64	–
Serine	3.29 – 6.84	2.46 – 5.60	2.2 – 6.6	4.73 – 5.10	–
Glutamic acid	15.49 – 32.77	13.25 – 15.68	3.8 – 8.9	11.11 – 11.51	–
Glycine	9.01 – 11.55	3.35 – 5.85	1.3 – 3.7	4.50 – 4.94	–
Alanine	3.41 – 11.59	4.75 – 7.34	2.5 – 5.6	6.77 – 7.63	–
Proline	3.10 – 9.67	5.03 – 29.45	–	7.90 – 8.87	–
Cysteine	1.02 – 5.70	0.63 – 0.85	–	0.41 – 0.61	–
Tyrosine	5.62 – 17.46	8.04 – 9.99	2.2 – 5.8	0.19 – 0.54	–
Asparagine	–	–	–	8.16 – 8.65	–
Total NEAA	51.24 – 124.10	43.69 – 97.04	14.4 – 38.8	48.76 – 53.49	**–**
SAA	1.74 – 9.61	1.47 – 2.11	–	0.88 – 1.19	2.2
AAA	7.49 – 22.15	9.23 – 13.89	3.4 – 14.0	3.73 – 4.70	3.8

SAA - sulfur amino acids (methionine + cysteine); AAA - aromatic amino acids (tyrosine + phenylalanine).

detected phenolic profile of MW using untargeted metabolomics approach based on ultra-high performance liquid chromatography with high-resolution mass spectrometry (UHPLC—HRMS), and then putative identified 171 phenolic compounds, including 16 anthocyanins, 10 flavan-3-ols, 18 flavonols, 39 flavones and other flavonoids, 60 other phenolics, 60 phenolic acids, and 7 stilbenes. Besides, authors indicated that MW was considered an abundant source of flavan-3-ols and stilbenes, with 3′-O-methylepicatechin and piceatannol being the most abundant compounds. Recently, Anusha & Negi (2025) detected 4 phenolic compounds in MW using HPCL, namely caffeic acid, gallic acid, vanillic acid, and syringic acid.

3. Application of MW in bakery products

As mentioned earlier, MW is a promising ingredient with high nutritional value, therefore, incorporation of MW to bakery products could improve the nutritional value of final products but also may provide potential health benefits to consumer. To this end, the current applications of MW in bakery products are concluded in this section and are presented in Table 5 and Fig. 2.

3.1. Bread

Bread is one of the most consumed staple foods worldwide and is important part of the daily diet (Zhang and Li, 2024). It is estimated that more than 9 billion kg of bread products are produced each year, and the average bread consumption per person is expected to 25.5 kg in 2025 (Mollakhalili-meybodi et al., 2023; Statista, 2025). Besides, bread is an important source of macronutrients (e.g. carbohydrate and protein) and micronutrients (e.g. minerals and vitamins) and is recommended in all dietary guidelines as part of a balanced diet (Dong and Karboune, 2021). Therefore, it is a good vehicle for fortification with other nutrients, contributing to a more healthy and balanced daily diet.

From Table 5, it can be seen that MW is mainly used as wheat flour substitution in bread development. Xie et al. (2022) investigated the effect of MW addition (5 %, 10 %, 15 %, and 20 %) on the high gluten dough rheology properties. The results showed that MW addition decreased the dough development time and dough stability time, but increased stretching resistance of the dough. In a further study, Xie et al.

Table 4
Content of dietary minerals in mealworm (MW).

Mineral (mg/100 g)	Noyens et al. (2024)	Mihaly Cozmuta et al. (2022)	Sikora et al. (2023)	Montalbán et al. (2022)	Bogusz et al. (2024)
Potassium (K)	767.22 – 1008.35	872.14	756 – 1000	1000 - 1220	1173.52 – 1334.22
Sodium (Na)	108.79 – 170.43	255.42	129 - 251	190 - 290	153.26 – 174.25
Magnesium (Mg)	165.15 – 308.63	324.36	145 - 251	160 - 240	260.79 – 305.43
Phosphorus (P)	649.69 – 915.07	216.32	483 - 640	720 - 860	–
Calcium (Ca)	33.63 – 61.89	225.07	94.1 - 238	60 - 110	65.45 – 73.16
Zinc (Zn)	8.86 – 11.27	53.05	9.38 – 12.6	9.44 – 17.00	17.16 – 20.04
Iron (Fe)	2.57 – 3.46	27.24	3.62 – 25.3	3.65 – 4.15	4.94 – 6.31
Manganese (Mn)	1.56 – 2.19	12.37	0.54 – 4.10	0.49 – 1.06	1.19 – 1.35
Copper (Cu)	–	18.65	1.13 – 2.82	0.86 – 1.37	2.32 – 2.66
Selenium (Se)	–	–	0.0474 – 0.0547	–	0.27 – 0.28

(2024) reported that MW incorporation improved the strength and stability of the medium-gluten dough, while it had adverse effect on whole wheat flour. In the study by Pérez-Rodríguez et al. (2023), investigated solid-state fermented MW (using *Aspergillus oryzae*) on the dough properties and bread quality, in comparison with unfermented MW. The results showed that fermentation decreased starch retrogradation value, indicating that fermentation could contribute to retard bread staling during storage. After 3-day storage, the fermented MW breads were softer than unfermented MW breads. In another study, Bottle et al. (2024) investigated the effect of the fat content of MW on bread dough properties. They substituted wheat flour by three types of MW flour (full-fat, partially defatted, and full defatted) at 10 % replacing level. The results showed that the fat in MW improved the dough stability. This could be attributed to the abundant phospholipids (51 %) in MW fat fraction (Bottle et al., 2024). Phospholipids are natural and can improve the ability of gluten to form a film and thereby increasing the dough stability (Tebben et al., 2022; Zhao et al., 2010).

In addition to the characteristics of bread dough, Kowalski et al. (2022) studied the physicochemical properties and sensory characteristics of bread incorporated with MW (10 %, 20 %, and 30 %). The results showed that MW addition enhanced lysine content of bread. Breads made with MW were darker, redder, and softer than the control bread (100 % wheat flour). Sensory evaluation showed that breads with 10 % of MW achieved organoleptic acceptance among consumers. In another study, Gantner et al. (2022) conducted on the nutritional, sensory, and microbiological qualities of breads enriched with MW (5 %, 10 %, and 15 %). The results showed that the addition of MW improved bread nutritional value in terms of protein and oil. In the microbiological analysis after 7-days of storage, the results showed that there were no differences ($p > 0.05$) in total counts of yeasts and molds between all reformulated breads (4.24 – 4.38 log CFU/g) and the control breads (4.28 log CFU/g). The sensory evaluation showed that the optimal addition level is 5 % in the bread. Furthermore, A. Jankauskienė et al. (2024) reported that the addition of MW improved essential amino acids content and monounsaturated fatty acids content in bread. In the sensory evaluation, results showed that higher addition levels could adversely affected consumer acceptance and caused more negative emotions (e.g. sad, angry, and scared). Additionally, Igual et al. (2021) analysed amino acids accessibility of enriched breads with MW using in vitro gastrointestinal digestion in three phases (gastric, intestinal, and at the end of digestion). The results showed that enriched breads had higher aminos acids release compared to the control bread, whereas the highest amino acids release from enriched breads occurred in the intestinal phase. Moreover, Mihaly Cozmuta et al. (2022) reported that the addition of MW comprehensively improved the bioaccessibility of minerals in bread, including sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), manganese (Mn), lithium (Li), and phosphorus (P), as determined by in vitro digestion analysis.

Hydrocolloids are supposed to be promising stabilisers in bread baking, which could contribute to improve bread quality (Ishaq et al., 2024; Zhao et al., 2021). Xie et al. (2023) utilised propylene glycol alginate (PGA) (0.3 %, w/w) in bread enriched with 10 % of MW (as wheat flour substitution). The results implied that PGA addition had positive effects on bread volume, porosity, hardness, cohesiveness, and springiness. Besides, PGA was found to slow down the staling process of bread during a 3-day storage test; in day 3, the hardness value of breads with PGA were lower than that of bread without PGA addition.

Celiac disease (CD) is a widespread autoimmune disease that is caused by the gluten ingestion in genetically predisposed individuals (Zingone et al., 2024). The symptoms of CD include diarrhoea, steatorrhoea, abdominal pain, fatigue, anaemia, and metabolic bone disease (Shiha et al., 2023). It is estimated that approximately 1 % of the global population is affected by CD during their life, and the only proven treatment is a strict gluten free diet throughout life (Discepolo et al., 2024; Lau et al., 2022). Therefore, gluten free products are important to meet consumer demand for healthier foods and strict gluten diet. Tauferová et al. (2024) developed composite gluten free bread using MW in combination with flaxseed, chia seed, psyllium, and apple fibre. The results showed that composite breads had higher total phenolic content and antioxidant capacity compared to the control bread (without any additional ingredients); In addition, in the sensory evaluation, composite breads had similar overall acceptance score compared to control.

3.2. Cookies

Cookies are one of the most popular bakery products, with diverse taste, convenience, affordability, and long shelf life (Molnar et al., 2023). Sriprablom et al. (2022) reported that the replacement of wheat flour by MW at 10 %, 20 %, and 30 % in cookie formulation. The inclusion of MW as wheat flour substitution increased the nutritional quality of the cookies in terms of protein, oil, and ash content. However, the reformulated cookies were darker, harder, and redder compared to the control. In terms of sensory evaluation, all sensory attributes decreased with increasing MW addition, while the 20 % replacing level was regarded acceptable as the overall acceptance score was higher than 5 points. Almost similar results were reported by Draszanowska et al. (2024) study, included MW as a substitute for mixed flour (oat flakes and whole wheat flour) in an oatmeal cookie formulation at replacement levels of 10 % and 30 %, respectively. The results showed that MW addition comprehensively increased nutritional quality of cookies, including content of monounsaturated fatty acids (MUFA), total phenolic, macrominerals (potassium, magnesium, and calcium), microminerals (zinc and iron), and antioxidant capacity. In terms of physical properties, the reformulated oatmeal cookies were darker and redder, but softer than the control. In sensory evaluation, the reformulated cookies at 10 % replacing level were well accepted.

Overall, these finding indicate that the potential incorporation of MW as wheat flour substitution in cookie development could produce high nutritional quality cookies. However, the colour parameters and texture properties of cookies are changed. Therefore, optimising the incorporation level of MW is necessary in further studies to produce cookies with desirable quality.

3.3. Biscuits

Biscuits are one of the most popular ready-to-eat snacks that are mainly made with wheat flour, fat/oil, and sugar (Hu et al., 2022).

Table 5
Applications of mealworm (MW) in bakery product formulation.

Product	Function	Usage level	Results	Refs.
Bread	Wheat flour substitution	10 %	i). MW addition increased content of protein, oil, potassium, magnesium, calcium, zinc, iron, and manganese. ii). Bread made with MW had higher bioaccessibility of minerals than that of the control bread (100 % wheat flour).	Mihaly Cozmuta et al. (2022)
Bread	Wheat flour substitution	10 % with propylene glycol alginate (0.3 %, w/w, as additive)	i). Propylene glycol alginate addition improved bread volume and texture. ii). Propylene glycol alginate addition slows down the bread staling process.	Xie et al. (2023)
Bread	Wheat flour substitution	10 %, 20 %, and 30 %	i). MW addition increased content of lysine and monounsaturated fatty acids, but decreased content of polyunsaturated fatty acids. ii). MW addition decreased hardness and lightness (L*), and increased bread volume (except for 30 % addition). iii). 10 % substitution level was acceptable in the sensory evaluation.	Kowalski et al. (2022)
Bread	Wheat flour substitution	5 %, 10 %, and 15 %	i). MW addition did not change bread volume and increase the risk of acrylamide ii). MW addition increased MUFA and total amino acid content, but decreased PUFA content. iii). In sensory evaluation, 5 % addition level of MW was acceptable.	A. Jankauskienė et al. (2024)
Bread	Wheat flour substitution	5 % of unfermented MW and fermented MW (*Aspergillus oryzae*)	i). MW addition changed dough rheology, resulted in a weakening of the gluten network. ii). MW addition increased bread nutritional value, but decreased bread volume and lightness (L*). iii). After 3-day storage test, breads made with fermented MW had lower hardness value than that of breads made with unfermented MW.	Pérez-Rodríguez et al. (2023)
Bread	Wheat flour substitution	5 %, 10 %, and 15 %	i). MW addition increased protein and oil content, and decreased lightness (L*) and hardness. ii). After 7-day storage, reformulated breads had similar total counts of yeasts and molds compared to the control (100 % wheat flour). iii). Breads made with 5 % MW was highest in overall sensory quality.	Gantner et al. (2022)
Bread	Wheat flour substitution	10 %	i). MW addition decreased lightness (L*) and yellowness (b*) of breads. ii). MW addition decreased bread volume, additionally, defatted MW breads had lower volume than full-fat MW breads. iii). MW addition increased protein and total essential amino acid content in bread. iv). The MW breads had lower in vitro protein digestibility than that of the control breads.	Bottle et al. (2024)
Bread	Wheat flour substitution	5 % and 10 %	i). MW breads had higher amino acids release than the control (100 % wheat flour), as determined by in vitro gastrointestinal digestion.	Igual et al. (2021)
Bread	High-gluten wheat flour substitution	5 %, 10 %, 15 %, and 20 %	i). MW addition decreased dough water absorption and strength, but increased dough stretching resistance and extensibility. ii). MW addition decreased lightness (L*) and increased redness (a*) and yellowness (b*) of bread. iii). Replacing wheat flour by MW at 10 % was satisfied to improve bread nutritional and physical properties.	Xie et al. (2022)
Gluten free bread	Functional ingredient	i). 2 % MW in combination with 4 % flaxseed, 2 % psyllium, 2 % chia seed, and 2 % apple fibre. ii). 2 % MW in combination with 8 % flaxseed, 2 % psyllium, 2 % chia seed, and 4 % apple fibre.	i). Composite breads had higher total phenolic content and antioxidant capacity than that of control breads. ii). Composite breads had similar overall acceptance score to the control breads.	Tauferová et al. (2024)
Chinese steamed bread	Medium-gluten wheat flour and whole wheat flour substitutions	5 %, 10 %, 15 %, and 20 %	i). MW addition decreased water absorption in both doughs. ii). MW addition increased medium-gluten dough stability, while it had undesirable effect on whole wheat dough. iii). MW addition changed colour parameter of medium-gluten steamed bread, but no impact on whole wheat steamed bread. iv). MW addition increased both steamed bread volume and decreased both steamed bread hardness, springiness, and cohesiveness. v). MW addition increased protein and oil content in both steamed breads.	Xie et al. (2024)
Cookies	Wheat flour substitution	10 %, 20 %, and 30 %	i). MW addition increased protein, oil, and ash content of cookie. ii). MW addition up to 20 % increased cookie hardness. iii). MW addition decreased lightness (L*) and increased	Sriprablom et al. (2022)

(*continued on next page*)

Table 5 (*continued*)

Product	Function	Usage level	Results	Refs.
			redness (a*) of cookie. iv). The shelf life of all MW cookies were more than 15 days. v). Cookie made up to 20 % was acceptable in sensory evaluation.	
Oatmeal Cookies	Oat flake and whole wheat flour substitution	10 % and 30 %	i). MW addition increased content of protein, oil, mineral, monounsaturated fatty acids, and total phenolic. ii). MW addition decreased hardness, lightness (L*) of cookie. iii). In sensory evaluation, cookie made with 10 % MW had similar score compared to control.	Draszanowska et al. (2024)
Biscuits	Wheat flour substitution	13 %, 17 %, 20 %, and 25 %	i). MW addition increased protein content of biscuit. ii). MW addition decreased thickness, lightness (L*), but increased hardness of cracker. iii). In the sensory evaluation, crackers made with 20 % MW had highest sensory score among other reformulated crackers.	Ortolá et al. (2022)
Biscuits	Wheat flour substitution	10 %, 15 %, and 20 %	i). 15 % MW biscuits had higher protein, fibre, and mineral content than control. ii). In vitro digestion analysis, 15 % MW biscuits had higher protein digestibility and lower starch digestibility than control.	Mihaly Cozmuta et al. (2023)
Crackers	Wheat flour substitution	2 %, 4 %, 6 %, 10 %, 15 %, and 20 %	i). MW addition decreased hardness and lightness (L*). ii). Crackers made with 6 % had higher ash, protein, and total phenolic acid content, as well as antioxidant capacity (DPPH and FRAP) compared to control. iii). Crackers made with 6 % MW had highest sensory score in terms of colour, aroma, and appearance.	Djouadi et al. (2022)
Crackers	Functional ingredient	5 %	i). MW addition increased protein, ash, and oil content. ii). MW addition increased total phenolic content and DPPH antioxidant capacity of crackers.	Ivanišová et al. (2023)
Butter Cakes	Functional ingredient	5 % and 10 %	i). MW addition decreased lightness (L*), redness (a*), and yellowness (b*). ii). MW addition increased protein content, hardness value, bur decreased springiness.	Hii et al. (2022)
Sponge Cakes	Wheat flour substitution	15 % and 30 %	i). MW addition increased protein, ash, fibre, and oil content of cake. ii). MW addition decreased lightness (L*), redness (a*), and yellowness (b*). iii). MW addition significantly increased total phenolic content and antioxidant capacity (DPPH, ABTS, and FRAP). iv). MW addition increased the intensities of sour, sweet, salty, and umami tastes of cake using electronic tongue analysis. v). 15 % MW addition level was accepted, which had similar sensory score to control.	Kowalski et al. (2023)
Pancakes	Wheat flour substitution	10 %, 20 %, and 30 %	i). MW addition increased protein, oil, lightness (L*), and redness (a*). ii). 10 % addition level was well accepted.	Mazurek et al. (2022)
Muffins		15 %	i). MW muffins had similar sensory qualities to the control muffins in terms of appearance, aroma, texture, and acceptance. ii). The sweet version of MW muffins had higher acceptance than savory version of MW muffins.	Mazurek et al. (2024)
Muffins	Wheat flour substitution	15 %	i). MW addition improved protein and oil content of muffins. ii). MW addition decreased muffin hardness, baking loss, and volume. iii). MW muffin was less lightness (L*) and more yellowness (b*) than control. iv). In the sensory evaluation, muffin containing with MW had rich nut smell and similar score with control in terms of flavour, colour, texture, and sweetness.	Çabuk (2021)
Muffins	Wheat flour substitution	Flour: 2 %, 6 %, and 10 % Whole insect: 6 %	i). MW addition changed colour parameters of muffins and increased total phenolic content. ii). MW addition decreased the glycemic index of muffins through in vitro analysis. iii). Muffins made with MW flour had higher acceptance than muffins made with whole MW.	Zielińska et al. (2021)

Ortolá et al. (2022) developed novel enriched protein biscuits with using 13 %, 17 %, 20 %, and 25 % of MW to replace wheat flour in formulation. Compared with the protein content of the control biscuits (7.8 %), all reformulated biscuits (16.11 % - 23.98 %) could be considered as "source of protein", especially when replacing level at 20 % and 25 %, they could be considered as "high in protein". The physical properties showed MW addition changed colour and texture of biscuits, making them darker and harder. Diabetes has become one of the fastest growing public health emergencies in the world (Hossain et al., 2024; Zhao et al., 2023). The International Diabetes Federation (IDF) report that approximately 589 million people had diabetes in 2024 and is expected to reach 853 million by 2050 (The International Diabetes Federation, 2025). Low glycaemic index (GI) food product could help consumer to manage postprandial blood glucose levels, which is regarded as one of effective strategies for preventing diabetes (Kumar et al., 2022; Zhang et al., 2021). Incorporation of MW in biscuit formulation has potential to produce low GI biscuits, which could have extra healthy benefits for consumer. Mihaly Cozmuta et al. (2023) evaluated in vitro starch digestibility and GI of reformulated biscuits with incorporation of MW, in comparison with the control biscuits (100 % refined wheat flour). They reported 15 % of MW addition resulted in a 1.09-fold decrease in total starch digestibility and 1.13-fold reduction glycaemic response, indicating the potential of MW to produce novel type of protein-enriched biscuits with lower GI.

3.4. Crackers

Crackers are thin, dry, crispy, and baked products and are a popular snake in the world due to their ready-to-eat convenience, long shelf life, low cost, and variety (Düşkün et al., 2025; Meriles et al., 2022). Crackers are usually made from unsweetened and unleavened dough, and main ingredients include soft wheat flour, salt, water, and fat (Düşkün et al., 2025). Djouadi et al. (2022) investigated the quality properties of crackers substituting wheat flour by MW. 6 % MW addition increased content of iron (Fe), zinc (Zn), potassium (K), protein, and total phenolic and antioxidant capacity (DPPH and FRAP). Similar results were reported by Ivanišová et al. (2023), they incorporated 5 % MW as wheat flour substitution in crackers, in comparison with the 100 % wheat flour crackers (control). The results showed that MW incorporation enhanced the content of essential amino acids in crackers, including threonine, leucine, isoleucine, lysine, histidine, valine, and phenylalanine. Regarding sensory evaluation at a 9-point hedonic scale, the aroma (6.05), taste (6.31), appearance (6.64), and overall acceptability (6.74) of the reformulated crackers were significantly lower that of the control crackers (7.06 of aroma, 7.22 of taste, 7.62 of appearance, and 7.42 of acceptability).

3.5. Muffins

Muffins are one of the popular bakery products widely consumed as snake or meal due to their soft texture, attractive taste, and simple preparation. In general, muffins are made of wheat flour, fat, sugar, milk, and egg (Xu et al., 2022). Although muffins can offer attractive taste and rich in fat and calories, they often lack sufficient in fibre, protein (Geraldo et al., 2024). Three studies have conducted on reformulated muffins using MW (Table 5). In a study conducted by Çabuk (2021), muffins were enriched MW (15 %, replacing wheat flour) and their nutritional quality, texture properties, and sensory attributes were determined. The results showed that MW addition increased protein and oil content, but decreased specific volume, lightness (L*), springiness, and cohesiveness. Notably, MW addition decreased hardness and baking loss, making it softer and helping increase in baking yield. In the sensory evaluation, all panelists stated that muffins with MW had a very rich nutty flavour, therefore, the score of odour was higher than the control. Besides, all sensory attributes of reformulated muffins were over 7, indicating that the muffins with 15 % MW was liked moderately.

The taste significantly influences the consumer acceptance and willingness to insect-based product, therefore, investigating consumers' dietary preference in taste for muffins can promote consumer acceptance (Lin et al., 2023). Mazurek et al. (2024) developed two flavour versions (sweet and savory) of muffins using 15 % of MW as wheat flour substitution and analysed the acceptance in both versions of muffins. The results showed that the sweet version of muffins (7.13) had higher acceptance score than that of savory version of muffins (6.56 %), indicating that sweet MW muffins were most conductive to acceptance in the market.

Besides, insect form is another important factor affecting consumer attitudes and acceptability. Zielińska et al. (2021) evaluated consumer attitude on incorporation of MW flour and whole MW to muffins. The results showed that muffins made with 6 % of MW flour (4.00) were more acceptable than muffins made with 6 % of whole MW (3.12) based on a 5-point scale. Therefore, they indicated that the understanding of consumers' dietary preference and habits is important to the development of insect-based products, which can help to improve consumer acceptance for these products.

3.6. Cakes

Cakes are one of the most typical sweet bakery products in the world. There is a great global demand for this product due to its attractive properties, such as being ready-to-eat, affordable, and diversity in taste (Gökçe et al., 2023). Same to other sweet bakery products, cakes are also deficiency in minerals, fibre, and bioactivity compounds. Hii et al. (2022) developed a new butter cake with incorporation of MW (5 % and 10 %) and its nutritional quality and physical characteristics was evaluated. The results showed that the protein content of butter cake increased with increasing MW addition, from 5.99 % (0 % MW addition) to 11.12 % (10 % MW addition). Moreover, MW addition decreased lightness (L*), yellowness (b*), and springiness, but increased firmness.

In another study, Kowalski et al. (2023) evaluated the chemical composition, antioxidant capacity, and sensory aspects of sponge cake with addition MW (as wheat flour substitution at 15 % and 30 % replacing level). MW addition comprehensively enriched nutritional quality of cakes in terms of protein, oil, ash, fibre, and total phenolic content. Besides, authors analysed the profile of phenolic compounds in cakes using high-performance liquid chromatography (HPLC) and found that incorporation of MW increased the content of gallic acid, vanillic acid, protocatechuic acid, protocatechuic aldehyde, and ellagic acid, but decreased the content of caffeic acid and *p*-coumaric acid. Regarding sensory aspects, MW addition enhanced bitter and umami taste, with 15 % of MW addition showed a high level of acceptability among the reformulated cakes.

In the study by Mazurek et al. (2022), they evaluated consumers' attitudes and acceptance towards the addition of MW (10 %, 20 %, and 30 %) as wheat flour substitution in pancakes. The results showed that all sensory attributes (i.e. taste, odour, structure, appearance, and preference) decreased with increasing MW addition level, except for the odour attribute of 10 % MW pancakes, which exhibited highest odour score among all bread samples. It was suggested that pancakes made with 10 % MW were well accepted among all reformulated pancakes. Besides, authors indicated that flavour was most important factor affecting the overall sensory acceptability compared to texture, aroma, and appearance.

4. Future perspectives

MW, an edible insect, is a promising and sustainable ingredient with rich nutritional value and has been shown to have great potential to be added to various bakery product formulations for nutritional fortification. Nevertheless, MW-based bakery products continue to face several challenges in practical application and in the human diet. Firstly, it should be emphasised that the incorporation of MW as wheat flour substitution and/or functional ingredient can significantly change the physical properties of the final products, including colour, flavour, and texture, the above properties could adversely affect consumer acceptance. Therefore, optimising the incorporation level of MW or the combination of MW with other ingredients and/or improvers (e.g. hydrocolloid and enzymes) to produce bakery products with satisfactory quality is important in further studies (Zhang et al., 2025).

Additionally, although consuming insects is commonly in many regions, they remain uncommon food ingredients in current daily diet and most consumers may never try edible insects and/or edible insect-based food products, which could evoke food neophobia and disgust for these reformulated products (Sogari et al., 2023). Besides, as mentioned earlier, taste is considered one of the most important drivers of food preferences. Therefore, more studies are needed to understand consumer preferred tastes (e.g. sweet and savory) and types of MW-based bakery products, thereby improving consumer consumption intention.

From the perspective of safety, MW contains many potential allergens, such as tropomyosin, arginine kinases, and hexamerin, which trigger allergic reactions in individuals who are allergic to crustaceans and mites (Villa et al., 2023). Processing methods may have potential ability to alter the allergenic properties of food allergens (De Marchi et al., 2021). However, the effects of processing are largely dependent on the processing conditions (e.g. temperature and time) and types of allergens (Pi et al., 2021; Yang et al., 2024). To this end, investigating the effects of different processing methods and their optimised processing conditions on the reduction of allergy risks of MW are worthing to explore more in future. A deeper understanding of processing methods would contribute to efficient utilisation of MW in food production and provide healthier and safer MW-based products.

5. Conclusions

With the rapid growth of population, investigating novel food sources is particularly important for ensuring food security. MW is considered a promising and sustainable food source with high nutritional values, such as protein, oil, minerals, and bioactive compounds. Resourceful utilisation of MW in the current food system will have significantly positive effects on addressing food insecurity and improving the sustainability of food system. Bakery products are prevalently consumed foods in the world and can be regarded as good vehicles for delivering nutrients in the daily diet. The incorporation of MW as wheat flour substitution and/or functional ingredient into bakery products presents great prospects in the development of novel sustainable health-promoting bakery products. However, MW-based bakery products are still under exploration. Improved knowledge on the potential nutritional value of MW and its progress in the development of bakery products could better promote its application and acceptability in the human daily diet.

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CRediT authorship contribution statement

Guoqiang Zhang: Writing – review & editing, Writing – original draft, Visualization, Investigation, Conceptualization. **Yuanhui Wang:** Writing – review & editing. **Zhangcheng Liang:** Writing – review & editing. **Jingyin Guo:** Writing – review & editing. **Bin Wu:** Writing – review & editing, Resources, Funding acquisition.

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

No data was used for the research described in the article.

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