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REVIEW

The Review of Cooking, Drying, and Green Extraction Methods on General Nutritional Properties of Mealworms and Locusts

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Abstract
The processing of edible insects as an alternative source of nutrition may be a key driver in the development of a sustainable food and feed system. This review will study two industrial types of insects–mealworms and locusts–and summarize evidence related to the impact of processing on their micro- and macronutritional characteristics. The focus will be on their potential use as food for human consumption as opposed to animal feed. Literature has indicated that these two insects have the potential to provide protein and fat qualities comparable to or better than traditional mammalian sources. For example, mealworms–the larval form of the yellow mealworm beetlepossess a higher fat content, while adult locusts are rich in fibers, especially chitin. However, due to the different matrix and nutrient compositions, the processing of mealworms or locusts at a commercial scale needs to be tailored to minimize nutritional loss and maximize cost efficiency. The stages of preprocessing, cooking, drying, and extraction are the most critical control points for nutritional preservation. Thermal cooking applications such as microwave technology have demonstrated promising results, but the generation of heat may contribute to a certain nutritional loss. In an industrial context, drying using freeze dry is the preferred choice due to its uniformity, but it can be costly while increasing lipid peroxidation. During the extraction of nutrients, the use of green emerging technologies such as high hydrostatic pressure, pulsed electric field, and ultrasound may provide an alternative method to enhance nutrient preservation.

Keywords Mealworms · Locusts · Cooking · Drying · Green technologies · Thermal

Introduction

The demand for animal-based food protein is projected to increase by up to 70% due to the exponential growth of the global population, which is estimated to reach 9 billion by the year 2050 (Yen, 2015). However, the global animal agriculture industry has been identified as a significant contributor to the climate crisis. For example, almost on the fifth of global greenhouse gas emissions are accounted by the livestock industry (Goodland, 2014). Over time, the production of animal livestock as food will continue to exhaust agricultural, water, forestry, fishery, land, and biodiversity resources (van Huis, 2013), resulting in irreparable environmental consequences. Therefore, edible insects may be a promising solution to alleviate the suite of pressing human health and environmental issues. Not only do insects emit fewer greenhouse gases, but they can also be reared on organic waste, thereby requiring only a fraction of water, feed, and space. In a circular

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economy, insects can also accelerate the decomposition of organic litter or animal feed. Furthermore, edible insects are highly nutritious and rich in proteins, fats, vitamins, and minerals. For example, approximately 76% of the daily human protein requirement is provided by 100 g of caterpillars (Rumpold & Schlüter, 2013), indicating that insects represent a strong potential source of an alternative protein. In animal husbandry, the feed conversion ratio (FCR) is a method of measuring the efficiency with which the livestock convert animal feed into the desired product. In comparison to livestock production, the FCR observed in edible insects is a much higher, meaning that they require less resource input and turn-around time.

For the past few years, the global market for edible insects has also gained strong interest and momentum. In the year 2018, the industry was estimated to be worth a total of 406 million USD and is predicted to increase to over 1.18 billion USD by the year 2023, with the North American market exhibiting the highest growth (Wade & Hoelle, 2020). Moreover, lower-income populations typically struggle to access high-quality dietary protein sources. The challenge to ensure adequate nutrition to these vulnerable cohorts has increased in difficulty due to the growing political instability in key food-producing countries, COVID-19 pandemic-induced global food supply chain disruptions, and worsening climate change. In Eastern Europe, the ongoing Russian-Ukraine war has driven up the price of commodities and staple foods, including wheat and corn, which were traditionally regarded as cheap nutrient sources. Additionally, climate change and export bans have led to poor agricultural yield and food security crises witnessed in several parts of the world, including Argentina, India, Ukraine, and Indonesia (Jayaswal, 2022).

This review will specifically discuss two types of insects used in the food industry: mealworms and locusts. These insects represent two out of four major species of insects that are scrutinized for industrialized mass production by *Protifam* and *Protix* of the Netherlands and *Bühler* Group of Switzerland, as well as Huis et al. (2017) (BuhlerGroup, 2022; Huis & Tomberlin, 2017; Protix, 2022). Other suggested families, which are flies and lesser mealworms, will not be covered in this review as they are more suitable as animal feed rather than human food. Although they are rich in nutritional composition with excellent growth abilities, their ferocious appetite for organic wastes such as manure renders them too risky for human consumption (Rumbos et al., 2019; Wang & Shelomi, 2017). With a proper combination with other ingredients, these insects are excellent alternatives to conventional animal feed (Wan-Mohtar et al., 2022).

Scientifically known as *Tenebrio molitor*, mealworms are the larval form of the beetle that thrives on stored grain. Therefore, it is often known as a pest but is revered for its excellent nutritional properties in circular food systems. Meanwhile, the locust-type family possesses tremendous potential as it is accepted religiously, especially by those who strictly adhere to Jewish (Kosher) or Islamic (Halal) principles. Similar to mealworms, certain locusts are a pest that can form swarms and are highly destructive to local crops. Therefore, the consumption of locusts can be highly beneficial not only for their nutritional values but as an effort toward pest management (Dobermann et al., 2017). In this discussion, cricket (*Acheta domesticus*) has been grouped with other locusts, mainly due to their similar physicality, order (*Orthoptera*), and nutritional properties.

To date, numerous studies have been conducted on the techno-functionalities, digestibility, nutrient composition, food safety, risk, and consumer perception of edible insects. However, the impact of specific processing methods on the nutritional properties of mealworms and locusts is still an expanding field. The effect of processing methods specifically the cooking, drying, and extraction technologies on the nutritional values (carbohydrates/fibers, proteins, fats, vitamins, and minerals) and the functionalities of mealworms and locusts will be discussed. Additionally, the impact of processing on minor non-nutritional compounds, such as antioxidants, will also be explored.

Mealworms and Locusts and Their General Nutritional Content

Typically, 6 major nutrients are important for human consumption. Micronutrients, such as vitamins and minerals, are required in minuscule amounts, and their role is well-defined in food systems. Macronutrients, such as carbohydrates, proteins, and fats or lipids, are essential not only for the amount but the qualities as well. Typically, insects are rich in protein (amino acids), fatty acids (monounsaturated and polyunsaturated), and fiber (chitin), and contain a satisfactory amount of minerals and vitamins, especially phosphorus and vitamin B complexes (Finke, 2015; Rumpold & Schlüter, 2013; van Huis, 2013). In contrast, they are low in simple carbohydrates and certain vitamins and minerals, such as vitamins A, D, and E, and calcium and iodine (Finke, 2002).

The range of the proximate composition of mealworms and locusts is shown in Table 1. However, their nutritional characteristics are largely dependent on the species, feed, growth stages, and rearing conditions. These have been demonstrated countless times in literature. For example, Finke (2015) showed that special diets could raise the level of vitamins A, E, and omega-3 fatty acids in crickets and mealworms for animal feed. Additionally, a temperature change was shown as an important factor in influencing the growth and feed pattern of insects and consequently led to different nutritional profiles (Lee & Roh, 2010).

Table 1 Macronutrients of edible insects. The values are extracted from previous literature reviews

Type of insect	Species	Proximate composition		
		Nutrient	Value (%)	Remarks
Mealworms[a]	*Tenebrio molitor* (9 literatures) 	Protein	47.18 – 65.29	Highest in adults, lowest in larvae
		Fat	14.88 – 43.08	Highest in larvae, lowest in adult
		Carbohydrate	0.01 – 7.10	Highest in larvae
		Crude fiber	5.00 – 20.22	Highest in adults, lowest in larvae
		Ash	2.36 – 4.3	Constant
		Energy (Kcal/100 g)	379.61 – 557.44	Highest in larvae and pupae
Locusts[a]	*Acheta domesticus* (7 literatures) 	Protein	55.00 – 70.75	Highest in adult
		Fat	9.80 – 24.00	Lowest in juvenile cricket
		Carbohydrate	2.12 – 3.93	Very low
		Crude fiber	6.20 – 22.08	Highest in adult
		Ash	3.55 – 9.10	Highest for juvenile cricket
		Energy	414.41 – 455.19	Constant
Locusts[b]	*Schistocerca gregaria* and *Locusta migratoria* (5 literatures) 	Protein	46.30 – 76.00	Highest in adult Poland locust
		Fat	7.70 – 32.30	Highest in adult Kenyan locust
		Carbohydrate	0.02 – 9.90	Very low except for Kenyan locust
		Crude fiber	2.50 – 11.00	Highest in adult Kenya locust
		Ash	3.30 – 6.70	–
		Energy	432.00 – 527.50	Highest in adult Sudan locust

Carbohydrate–measured as a nitrogen-free extract, calculated by the difference with other proximate measurements (protein, fat, fibers, ash, and moisture)

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[a](Rumpold & Schlüter, 2013)

[b](Egonyu et al., 2021)

Furthermore, as proximate components are particularly sensitive to the techniques and procedures used, the values are not comparable if the analysis is not performed by the same person under the same conditions. Therefore, it is virtually impossible to define the macronutrients of edible insects based on literary sources. Even so, the question arises as to what this summary for a group of species will be when it is also known that individual species of "locusts" or "mealworms" differ significantly in the content of macronutrients. Nevertheless, knowing their approximate amount will be beneficial for processing and nutritional purposes.

High protein content has been observed in insects ranging from 7 to 48 and 13 to 27/100 g fresh weight, respectively. Mealworms and locusts have a similar average protein content, around 46–76%, although it comes from different order (Table 1). House cricket (*Acheta domesticus*) has up to 65% average protein content with a high-quality essential amino acids score, which is significantly higher than many animals and plant proteins, while also being more balanced in terms of carbohydrate, energy, saturated fat, and sodium content (Nowakowski et al., 2022). As the protein is high, additional enzyme hydrolysis or processing may produce a high amount of bioactive peptides (Nongonierma & FitzGerald, 2017; Zielińska et al., 2017), which can also contribute to antioxidative properties (Di Mattia et al., 2019). Although many amino acids are in excess, certain amino acids can be quite low in these insects, such as methionine, serine, and tryptophan (Hackewitz, 2018), and enriching their feed may overcome the deficiency (Khan, 2018).

The content, composition, and degree of lipid saturation, as well as the presence of cholesterol in insects, are highly dependent on species, development stage, and origin of the material used for fatty acid analysis. Fatty acids in insects originate from the dietary lipid absorption either through midgut epithelium or from sugars in their enterocytes and are usually the highest during the final larval stage, especially in mealworms (Oonincx et al., 2020). In crickets, the number of fatty acids was 13.4% of their dry matter (Rumpold & Schlüter, 2015), which is lower compared to typical conventional meats that contain more than 35% of fatty acids value (Muzolf-Panek & Kaczmarek, 2021). The fatty acid profile of insects is similar to that of vegetable oils and animal fats (Sosa, 2017). Furthermore, Zielińska et al. (2015) stated that insects are rich in unsaturated fatty acids, especially polyunsaturated fatty acids (PUFAs), and the amount is comparable to other food sources like poultry, fish, and shrimp. For example, mealworms can have up to 74.64% PUFA content, as opposed to other adult species such as *Gryllodes sigillatus* (tropical house cricket) at 66.24% and desert locusts at 64.63% (Zielińska et al., 2015). Likewise, Sosa (2017) mentioned that unsaturated fatty acids make up 75–76% of total fatty acids in whole larvae of mealworms.

However, the ratio of omega-6/omega-3 (n-6/n-3) in the mealworm lipids (18:1) and *Gryllodes sigillatus* (14:1) are relatively high compared to the ratio recommended by the FAO (10:1) (Zielińska et al., 2015). Oonincx et al. (2020) reported that commercially produced insects have higher levels of n-6 fatty acid compared to the ones that are collected from the wild; the desirable n-6/n-3 (lower) ratio could be achieved by adding 1–2% of flaxseed oil to enrich their standard diets. Apart from that, insects may lack certain essential fatty acids, such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA), which is typically found in seafood (Dobermann et al., 2017).

Table 1 also indicates that the protein and carbohydrate contents in mealworms and locusts are quite similar, but the range ("standard deviation") varies greatly amongst the literature. Like other animals, these insects have low carbohydrate content. Son et al. (2021) found that the total carbohydrate content of mealworms was only 11.7%, which is significantly lower than other animals like chicken or pork. Additionally, only 30% is in form of total soluble sugar, especially fructose, which indicates the lack of its roles toward sensorial properties (Son et al., 2021). Nevertheless, this value is considerably higher than previously reported literatures, whereby only 0.01% carbohydrate can be found in adult mealworms, while larvae recorded the highest at 7.10% (Rumpold & Schlüter, 2013). Even among insects, mealworms are considered to have the lowest percentage of carbohydrates, on par with ant *Atta mexicana* and the bug *Euschistus strennus*. Similarly, locusts contain low carbohydrates, mostly below 10% (Egonyu et al., 2021; Rumpold & Schlüter, 2013).

Most of the carbohydrate content in insects is in the nondigestible form of chitin (Jantzen da Silva Lucas et al., 2021). Marei et al. (2016) reported that locusts have the highest yield of chitin (12.2%) in their exoskeleton among other animal sources, including shrimp (10.0%), beetles (5.0%), and honeybees (2.5%). Chitin is popular as a functional food component composed of a long-chain polymer of N-acetylglucosamine with 90.6% of total dietary fiber (Maezaki et al., 1993). The insect species and their development stage influence chitin content, whereby an estimate of 81.5 and 137.2 mg/kg of chitin were observed in cricket nymphs and adult mealworms, respectively (Finke, 2007).

Other than cellulose, chitin is regarded for its derivative, namely, chitosan, which is obtained from the partial deacetylation process of chitin under alkaline conditions (Jantzen da Silva Lucas et al., 2021). Chitosan can serve as prebiotics, thus improving gastrointestinal health, producing beneficial short-chain fatty acids, modulating gut microbiota, reducing pathogenic microorganisms, improving immune system responses, and supporting weight management (Stull et al., 2018). Furthermore, other biological effects such as antimicrobial, antioxidant, anti-inflammatory, anticancer, and immunostimulatory activity have also been demonstrated (Nowakowski et al., 2022).

Apart from macronutrients, insects contain a wide range of micronutrients, including vitamins and minerals, depending on their species, breeding conditions, and stage of development. They are rich in vitamin B complex but low in vitamins A, C, and E. For example, the grasshopper (locust) is found to have a consistent level of vitamin B during all stages of development, while levels of vitamins A, C, D, and E are only directly proportional to its stages of maturity (Ordoñez-Araque & Egas-Montenegro, 2021). Fortifying the diet of the insects could also transform them into vitamin-rich food products like tea, containing 15.05 mg per 100 g of vitamin C (Rumpold & Schlüter, 2013). However, in some cases, simply modifying their feed may not make up for these deficiencies. For example, increasing vitamin C in the diet of some insects may interrupt their life cycle and even lower the viability of delivered eggs (Etebari & Matindoost, 2005).

As for minerals, Ordoñez-Araque and Egas-Montenegro (2021) reported that insects usually have the potential to provide specific macronutrients such as calcium, phosphorus, and magnesium. For example, the cricket, *Onjiri mammon*, is able to provide a sufficient amount of iron for human consumption. In some instances, the levels of minerals such as iron in edible insects can be superior to beef (Latunde-Dada et al., 2016). Although some of it contains low sodium content, it could be used as a part of daily intake for individuals that are sensitive to high levels of sodium (Imathiu, 2020). However, without a mineralized skeleton, the invertebrates may have very little calcium content (Ojha et al., 2021). In addition, low heavy metal is observed in grasshopper, indicating it is safe for human consumption (Kouřimská & Adámková, 2016).

The Effect of Cooking Methods on the Nutritional Properties of Mealworms and Locusts

Insects can be further processed via cooking or conversion into powder form to enhance their organoleptic and food safety qualities. The manufacture of insect-based food generally starts with the post-harvesting of raw insects, followed by necessary processing steps. After receiving, insects must undergo a starvation period (or gut emptying) to minimize microbial load from intestinal fecal contents, which is crucial for eliminating several food safety risks and improving the quality of finished products (Mancini et al., 2020).

Following starvation, the edible insect undergoes various preprocessing steps involving assortment and detachment of residuals from substrates, killing, removal of unnecessary parts such as wings or legs, and cleaning (Rumpold & Schlüter, 2013). The insects are then subject to a variety of processing operations depending on the desired final product, which can be in a wet or dry form. The common methods employed to produce insects as food at an industrial scale consist of blanching, drying (oven dryer), roasting, freezing, fermentation, and milling. Currently, most published articles recommend spray drying and freeze drying as efficient processing technologies for insect-based food (Melgar-Lalanne et al., 2019).

After the pretreatment of insects, the next step is commonly cooking for direct consumption. Apart from increasing palatability, cooking ensures the safety and digestibility of insects. However, it could have a deleterious effect on its nutritional content. Traditionally, insects are prepared by simple cooking methods such as boiling, roasting, frying, and steaming. A summary of the effect of different cooking styles on the nutritional and non-nutritional properties of mealworms and locusts is illustrated in Table 2.

There are some discrepancies in recent literatures regarding the effect of cooking on the nutritional changes in insects (Fig. 1), as demonstrated by the different colors across the heat map. For example, Manditsera et al. (2019) and Mancini et al. (2021) found that boiling reduces protein digestibility, but Caparros Megido et al. (2018) found an increase instead, although it can be attributed to the different insects (mealworms versus locusts) being used. As cricket is rich in sulfur amino acids, the protein aggregation caused by the formation of disulfide bonds is more prominent, thereby reducing its digestibility during heat treatment (Manditsera et al., 2019). However, it is also known that mealworms are also rich in sulfur amino acids (Cláudia da Costa Rocha et al., 2021), but the different outcome may stem from the richer fat composition in mealworm larvae. Although heat is typically associated with lower protein digestibility, some literatures have noted that it may work differently in different food materials by unfolding the protein and aiding proteolytic enzymes (Tang et al., 2022).

The impact of cooking on total crude proteins is also unclear. Ssepuuya et al. (2020) reported an increase in grasshopper protein due to loss of fat, while Manditsera et al. (2019) illustrated that the protein content of cricket was decreased with boiling time, attributed to leaching of protein or by the hydrolysis of proteins. Similarly, the impact of cooking on minerals is also still unclear, possibly due to the limited literature available. Manditsera et al. (2019) and Baek et al. (2019) found that the bioavailability or content of certain minerals (iron and zinc) can be reduced, while Ssepuuya et al. (2020) found an increase in the mineral content. Therefore, it could be concluded that different species or techniques largely affected the outcome, and more studies are needed to confirm the findings.

In general, frying may be the least desirable processing method due to the absorption of cooking oil, which may lead to changes in nutritional profiles, lipid oxidation, and eventual rancidity. PUFAs were shown to dominate as frying is applied (Caparros Megido et al., 2018; Mancini et al., 2021), at the expense of short-chain fatty acids (SFA), but the contrasting observation was reported by Ssepuuya et al. (2020). The increase in PUFAs during frying may be caused by the absorption of cooking oil. An increase in lipid content may lead to autoxidation and induce protein-lipid aggregate, which reduce proteolysis (Caparros Megido et al., 2018; Mancini et al., 2021).

David-Birman et al. (2018) demonstrated that different types of thermal cooking might contribute to different

Table 2 The changes in nutritional and non-nutritional qualities of selected edible insects under different cooking styles

Insects	Cooking style	Nutritional findings	References
Mealworms	Boiling, pan frying, vacuum cooking, and oven cooking	Vacuum cooking and boiling produced low microbial load and high levels of digestible protein and PUFAs, but pan frying increased lipid content	(Caparros Megido et al., 2018)
	Deep frying, microwaving, boiling, and steaming	All cooking types decreased SFA and MUFA content, but deep frying caused the most significant changes in digestibility, FA profiles, and oxidative status	(Mancini et al., 2021)
	Freeze drying, hot air drying, oven broiling, roasting, pan frying, deep frying, boiling, steaming, and microwaving	Deep frying significantly reduced mineral composition, while microwaving reduced vitamins B1 and B3. Antioxidant activities moderately increased in all samples, especially in the freeze-dried sample	(Baek et al., 2019)
	Roasting at 4 different time points	Increased oleic acids and δ-tocopherol contents, but decreased linoleic acid and α- and γ-tocopherol contents. Increased oxidative stability	(Jeon et al., 2016)
	Blanching and fermentation with *Bactoferm® F-LC* or with the pure culture *Lactobacillus farciminis*	All treatments lead to impaired functional properties, lower molecular mass proteins, and higher free amino acids	(Borremans et al., 2020)
Mealworms and locusts (cricket)	Raw, boiled, and baked	The antioxidant activities of insect hydrolysate increased after heat treatments	(Zielińska et al., 2017)
	Baked (into muffins)	Increased proteins and antioxidants, lowered carbohydrates and glycemic index	(Zielińska et al., 2021)
Mealworms and locusts (grasshoppers)	Fermentation with *Lactococcus lactis*	Increased polyphenol, antioxidant, peptide profile, and hypertensive activities	(Mendoza-Salazar et al., 2021)
Locust (cricket)	Roasting, wet heating, and microwaving	Crude protein was the highest in microwaving, wet heating produced the highest crude fat and ash, and roasting produced the highest soluble fiber	(Tinarwo et al., 2021)
	Boiling, roasting, or combined boiling and roasting	Roasting is superior to other methods because of higher protein digestibility and mineral accessibility	(Manditsera et al., 2019)
	Baking	Baking did not alter the allergenicity of cricket allergen	(De Marchi et al., 2021)
Locusts (grasshopper and cricket)	Frying and roasting	To produce more proteins, roasting and frying are suitable for grasshoppers and cricket, respectively	(Porusia et al., 2020)
Locusts (grasshopper)	Boiling and roasting	Does not alter amino acids and fatty acid profiles but increases mineral content. Boiling reduces vitamin B12 by 70–85%	(Ssepuuya et al., 2020)
	Toasting and solar drying	Reduced protein digestibility and niacin/vitamin B3	(Kinyuru et al., 2010)

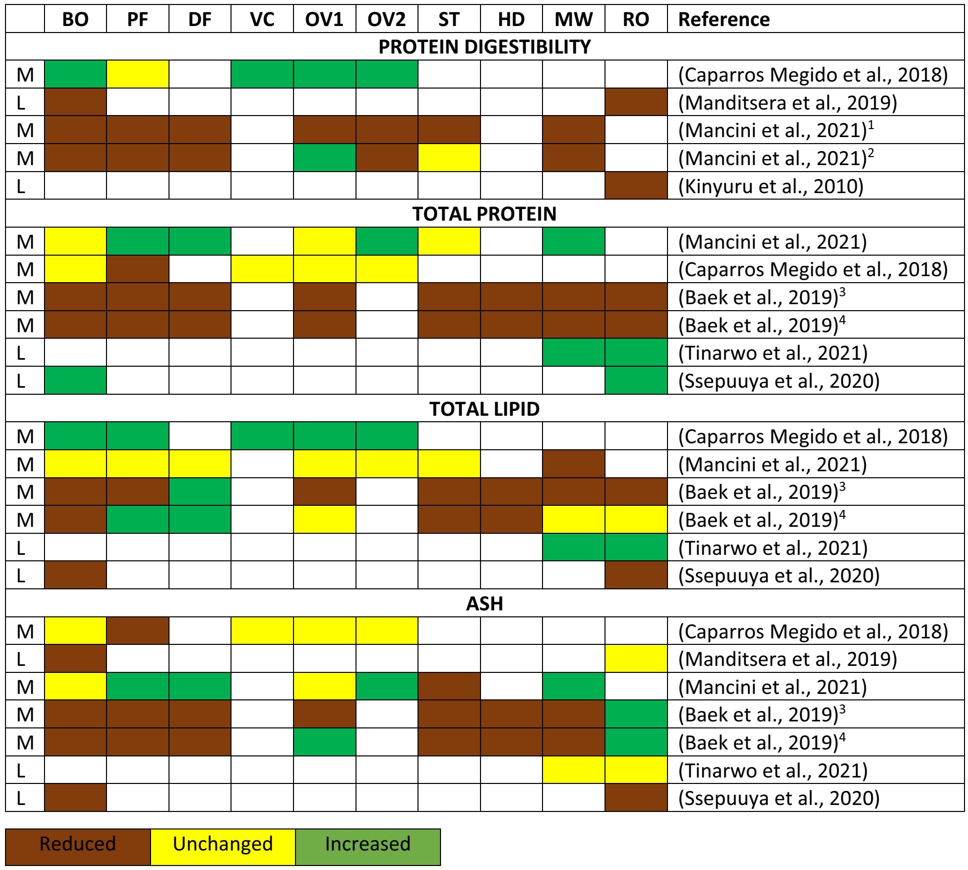

Fig. 1 The heat map showing the impact of heat treatments on the protein digestibility, lipid, and ash content of mealworms (M) and locusts (L) from selected publications. The nutritional changes are compared to their respective control experiment, which is typically uncooked or raw insects. BO, boiling; PF, pan fry; DF, deep fry; VC, vacuum cooking; OV1, oven cooking, lower limit; OV2, oven cooking, upper limit; ST, steaming; HD, hot-air drying; MW, microwave; BL, blanching; BA, baking; RO, roasting; [1]in vitro digestibility; [2]in duodenal digestibility; [3]cook with moisture; [4]cook without moisture

proteolytic outcomes. In this study, baking increased gastric proteolysis while other thermal cooking methods did not, especially when reducing sugars are present that may induce the Maillard reaction and protein aggregation. Jeon et al. (2016) showed the shift of unsaturated fatty acids into saturated fatty acids as a longer roasting time is applied. Meanwhile, moist heat such as boiling will affect water-soluble vitamins, as they can leech out into the water during the preparative process (Baek et al., 2019; Ssepuuya et al., 2020). In terms of antioxidant abilities, thermal cooking methods generally reduce their electron transfer but improve their proton donor ability (David-Birman et al., 2018).

The Impact of Drying Using Thermal and Nonthermal Treatments

The stability and safety of food products are highly dependent on the moisture content and level of water activity (a_w). High a_w and moisture supports the risk of microbial growth and increases the rate of chemical and enzymatic reactions, which will affect the product's nutritional properties. Since ancient times, drying has been conducted with the principal purpose of preserving food and agricultural by-products. In edible insects, drying increases the microbiological quality, reduces the risk of rancidity, and improves the color and texture of the final products. In industrial applications, drying is performed after pretreatments to improve shelf life during transport and storage (Vandeweyer et al., 2017). Traditionally, blanching is used for the treatment of insects prior to drying. The blanching step greatly reduces microbial contamination and future enzymatic activities such as lipid peroxidation and browning reaction (Wynants et al., 2018). Overall, the summary of the heat and non-heat applications on the nutritional properties of mealworms and locusts based on the recent literature is illustrated in Fig. 2.

Freeze drying, which dries whole insects by removing the ice by sublimation, is typically used in industrial practice to achieve rapid and consistent quality of end-products. A study by Kröncke et al. (2019) found that freeze drying of mealworms produced a diverse spectrum of volatile compounds and lipid oxidation intermediates in comparison to rack-oven drying. Previously, their team had found that the alternative to freeze drying, such as microwave, fluidized bed, and oven drying, all significantly reduced protein solubility in mealworms, likely due to the heat that induced the Maillard reaction and protein oxidation (Kröncke et al., 2018). The Maillard reaction was further proven as the mealworms turned darker as higher heat was

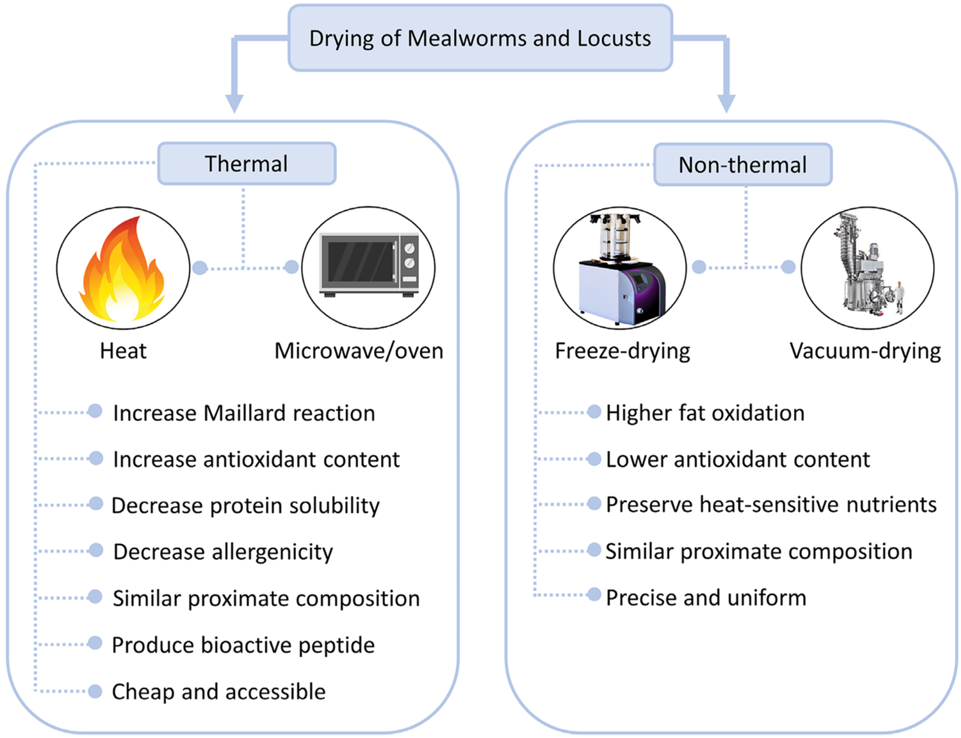

Fig. 2 The summary of thermal and nonthermal impacts on the drying of mealworms and locusts

applied (Kröncke et al., 2019). However, in a study by Fombong et al. (2017), the uses of either freeze dry and oven drying on different grasshoppers induced only little change in their proximate composition, but their chitin was reduced during freeze dry (Fombong et al., 2017). This was also observed by other authors, which observed little total protein difference between conventional thermal treatments and freeze dry, indicating that heat played a major role in solubility but not the total proteins of insects (Lucas-González et al., 2019; Mishyna et al., 2020; Selaledi & Mabelebele, 2021).

Although freeze drying may preserve heat-sensitive compounds, the productivity of the freeze-drying process is rather low due to the high cost. For example, Keil et al. (2022) demonstrated that freeze drying 1 kg of mealworms cost an energy equivalent of 4.69 EUR/kg, which is significantly higher than microwave drying (2.16 EUR/kg), infrared (0.99 EUR/kg), and oven drying (0.88 EUR/kg) (Keil et al., 2022). Hence, the practice of freeze drying is both capital and energy intensive and may be a limitation for certain stakeholders involved in the production and/or processing. Apart from the lower cost and reduced energy input required, microwave drying was shown to be a great alternative to freeze drying as similar proximate values and a_w were observed (Kröncke et al., 2018; Lenaerts et al., 2018), except lower protein solubility as previously mentioned. Furthermore, no vacuum condition was needed, which consumed most of the energy. It also resulted in lower a_w at below 0.60, which is necessary to eliminate microbial growth (Vandeweyer et al., 2017).

A study by Jensen et al. (2019) demonstrated that freeze-dried mealworms scored the highest crude protein digestibility-corrected amino acid score (PDCAAS), a measure that has been used to test the quality of proteins in rats. Microwave-dried mealworms showed average protein quality, while vacuum-drying and acid hydrolysis produced the lowest protein quality. Overall, mealworms scored better than lesser mealworms upon processing (Jensen et al., 2019). Likewise, a higher and consistent amount of bioactive peptides (ACE and DPP-IV) were obtained from cricket to produce bioactive peptides by employing microwave-assisted enzymatic hydrolysis. These bioactive peptides were also found to exhibit lower allergenicity (tropomyosin-IgG) compared to those extracted using conventional heating. Further analysis revealed the changes in the allergen protein Amid-I and S-S region due to microwave heating (Hall & Liceaga, 2020).

Higher fat oxidation status is often linked to thermal treatment as it accelerates certain chemical reactions, such as the formation of free radicals and pyrolization. Interestingly, both Lenaerts et al. (2018) and Kröncke et al. (2018) concluded that freeze drying induced higher fat oxidation status rather than thermal treatment in mealworms based on peroxide value and 4-Hydroxynonenal evaluation, respectively. A later study also confirmed this finding (Keil et al., 2022). Subsequently, this led to lower antioxidant content and an increase in lipid oxidation products. Generally, the lipid oxidation potential decreases as a_w becomes lower but may increase again once the value drops below 0.3. This observation is more evident with the freeze-drying method, which can drop a_w too low and re-induce lipid oxidation (Kröncke et al., 2018). The GC-MS analysis of the freeze-drying method revealed that this process produces higher secondary (e.g., aldehydes) and tertiary (e.g., 2-alkylfurans and methyl ketones) lipids, which are believed to be the reason for a higher status of fat oxidation. In turn, these products induced the Strecker-like enzymatic degradation of branched-chain amino acids involved in the Ehrlich pathway, which is apparent in the production of 2-methylpropanal, 3-methylbutanal, and 2-methylbutanal (Keil et al., 2022).

In contrast, the application of heat-induced nonenzymatic browning shifts away Strecker aldehydes toward Maillard products such as 2-methylpropanoic acid, 2-/3-methylbutanoic acid, and alkylpyrazines. The Maillard reaction might have also occurred due to the presence of amino sugars such as chitin, chitosan monomers, and intermediates between Maillard and lipid oxidation products such as pyrazines during the thermal processing of insects (Keil et al., 2022). Interestingly, heat-related drying techniques were found to increase the antioxidant capacity of processed insects in certain cases. Although heat is known to degrade nutrients and non-nutrients, the reformation of antioxidant compounds (Kröncke et al., 2018) or the degradation of proteins into bioactive peptides during thermal treatment may be possible (Zielińska et al., 2017). However, findings of these quantitative studies (TEAC, DPPH, and FCR) should be further affirmed by qualitative investigation (e.g., ABTS coupled with HPLC-ESI-ToF-MS) that can identify enzymatic and nonenzymatic antioxidants, which are highly desirable in the study of complex food matrices.

In a study by Huang et al. (2019), it was found that both conventional and microwave drying retained more than 40% of essential amino acids while having a good digestible indispensable amino acid score (DIAAS) of over 75% in mealworms and crickets. The presence of aspartic and glutamic acids as dominant amino acids can positively influence the overall sensory experience. However, it is noted that conventional drying produced better DIAAS than the microwave due to the polymerization of protein particles (Huang et al., 2019). Nevertheless, these techniques managed to produce amino acids that far exceeded the FAO/WHO recommendation (FAO/WHO, 2013). This indicates that different amino acid compositions and digestibility can be achieved using different drying methods during the processing of proteins from insects.

Recently, an interesting approach using pulsed electrical field (PEF) combined with far-infrared radiation (FAR) was employed to overcome the drawbacks of slow, energy-consuming, and quality deteriorations typical of other thermal-related drying processes (Bogusz et al., 2022). As FAR application bypasses the need to heat the air, the heat transfer is more efficient and precise, with higher energy absorption by the food matrix. In this study, the mealworm larvae were pretreated with PEF to improve the kinetics of water evaporation during the FAR drying. Overall, physical properties were improved except for an increase in hygroscopic properties. However, the only nutritional property measured was the soluble solids, which were minimally affected by this combinatory treatment (Bogusz et al., 2022). A more detailed study was conducted on the black soldier fly, whereby a gentle PEF pretreatment led to a faster drying rate and enhancement of fatty acid profiles, yield, and physicochemical properties (Alles et al., 2020). The insect nutrients, especially mealworms, are suitable for these treatments due to the more uniform distribution of fat in the larval tissue, which leads to a lower quality loss in the form of soluble solids.

The Effects of Green Emerging Extraction Methods on Nutrition and Functionalities of Mealworms and Locusts

The extraction step is crucial to enhance the nutritional status of edible insect products in the food industry. Typically, the use of traditional extraction methods on proteins or fats involves the use of aqueous solvents with pH modification. Hexanal extraction of lipids can yield up to 96% oil but is not environmentally friendly (Gravel & Doyen, 2020). Recently, the use of emerging technologies, mainly nonthermal procedures, has been explored, as research is indicating that they may provide profound advantages in improving shelf life, minimizing organoleptic changes, and promoting sustainable eco-friendly processes (Hameed et al., 2018; Tokuşoğlu & Swanson, 2014). The extraction processes can be divided into two categories: conventional (aqueous) or green methods (enzyme, pressure, microwave, electric, and sound), which are often combined to achieve maximal output. Some green methods, for example, supercritical CO_2, can match the extraction yield of the solvents but might be too expensive to be used at an industrial scale at this stage (Gravel & Doyen, 2020).

Table 3 demonstrates the effect of green extraction methods–ultrasound-assisted extraction (UAE), pulsed electrical field (PEF), high hydrostatic pressure (HHP), pressurized liquid extraction (PLE), supercritical fluid extraction (SFE), and microwave extraction (MWE)–in mealworms and locusts. In Table 3, most authors focused on the analyses of protein, fats, and other non-nutritive characteristics like antioxidants, which is understandable considering the purpose of extractions (for protein or defatting). There is little focus on carbohydrates and other micronutrients; therefore,

Table 3 A summary of green technologies impact the nutritional properties of mealworms and locusts

Method	Insect	Protein	Fat	Others	Reference
UAE	M	-	-	↑ α-glucosidase inhibitory peptides	(Rivero-Pino et al., 2020)
	M	-	↑ oxidative stability with lower peroxide and FA compositions	↑ antioxidants at 70 °C	(Gharibzahedi & Altintas, 2022)
	M	↑ amino acids, the efficiency of hydrolysates and new peptides, protein yield	-	-	(Cláudia da Costa Rocha et al., 2021)
	L	-	↑ fatty acids profile	-	(Otero et al., 2020)
	L	↑ solubility and the techno-functional properties	-	-	(Cruz-López et al., 2022)
	L	↑ yield and protein recovery	-	↑ antioxidative capacity	(Kingwascharapong et al., 2021)
		-	↑ lipid profile of atherogenic and thrombogenic indices, ↓ cholesterol enrichment	-	(Otero et al., 2020)
HHP	M and L	↓ protein solubility as temperature increases	↑ extraction yields of Ω-3 and Ω-6 FA	↑ cricket antioxidant activities and phenolic compounds	(Bolat et al., 2021; Ugur et al., 2021)
	M and L	↑ protein solubility of M, ↓ for L	↑ oil binding for M	-	(Dion-Poulin et al., 2020)
	M	↑ protein solubility, aggregation, and reduce antigenicity	-	-	(Boukil et al., 2020, 2022)
	M and L	-	Comparable SFA, MUFA, and PUFA with solvent extraction, but with unique compositions	-	(Ugur et al., 2021)
SFE	M and L	-	↑ volatile compounds related to flavor	Modified chitin structure and texture	(Sipponen et al., 2018)
	M	-	↑ lipid profile and oil stability	↑ immune system	(Cláudia da Costa Rocha et al., 2021)
PLE	M and L	-	↑ MUFA, ↓ PUFA, and SFA	Inhibit pancreatic lipase	(Otero et al., 2020)
MWE	L	↑ functional peptides	-	-	(Hall & Liceaga, 2020)
PEF	L	↑ extraction yields of protein	↑ extraction yields and properties of fats	↑ antioxidant activities	(Psarianos et al., 2022)

↑ increase, ↓ decrease, *M* mealworms, *L* locusts, *UAE* ultrasound-assisted extraction, *HHP* high hydrostatic pressure, *SFE* supercritical extraction, *PLE* pressurized liquid extraction, *MWE* microwave extraction, *PEF* pulsed electrical field

more research on these unexplored areas would be beneficial to understand the whole effect of extractions on their nutritional properties.

Generally, UAE is a versatile process that uses mechanical acoustic waves generated by high-frequency sounds and a liquid solvent as a medium to accelerate the extraction of compounds present in a food matrix (Herrero et al., 2012; Lempriere, 2003). In the food industry, this technique can be used at a low intensity (> 100 kHz) or high intensity (20–100 kHz) (Herrero et al., 2012; Ojha et al., 2021). Recently, this technology has been reported to be beneficial as a pretreatment before drying to achieve optimal extraction of lipidic fractions from edible insects (Hernández-Álvarez, 2021). For example, Otero et al. (2020) demonstrated that the UAE of mealworms and crickets produced higher yields of lipids compared to PLE. UAE displayed superior qualities in all lipid parameters tested on both insect extracts. The parameters tested were enrichment of PUFA (due to enrichment of linoleic acid), PUFA/SGA ratio, atherogenic and thrombogenic indices, and reduced cholesterol level. Nevertheless, pressurized liquid extraction produced the highest yield in both insects due to the presence of specific carbon number fatty acids in these insects (Otero et al., 2020). Despite PLE being indicated to produce a better lipid profile in selected marine organisms, this was not observed in mealworms and crickets, possibly due to the unsuitability of solvents or other parameters (Otero et al., 2020).

A study by Rivero-Pino et al. (2020) analyzed the production of bioactive peptides using UAE and coupled them with enzymatic treatments to add value to the mealworm hydrolysates. The proteins were unraveled by the ultrasound while the native protein was cleaved by subtilisin and trypsin. These were performed using an optimal time and correct sequential enzymatic hydrolysis to release the α-glucosidase inhibitory peptides (antidiabetic peptides) as well as to avoid low bioactivity. Mealworm larvae extract has been demonstrated to possess antiproliferative (therefore anticancer) properties against Caco-2 and HepG2 cells before (Ding et al., 2021). It is hypothesized that the presence of a myriad of amino acids in mealworms, such as carnosine, sulfur- and hydrophobic-amino acids, may contribute to this effect as mysore thorn borer aqueous extract did not exhibit a similar outcome due to a much inferior amino acids profile in comparison to mealworms.

In grasshopper, the application of UAE to increase the sensorial experience while increasing functionalities in meat products was demonstrated by Cruz-López et al. (2022). In this study, the grasshopper extract from alkalization or alkalization-piezoelectric sonication was used as a meat extender in the meat sausage. The extension was able to increase protein solubility and techno-functional properties of soluble grasshopper protein, especially at 10% concentration, while 5% concentration gave the optimal sensory experience in comparison to normal meat sausages. The application of UAE may have facilitated the formation of cross-links between protein strands or protein-coated oil lipids, thus improving the viscoelastic, gelling, textural, and rheological properties.

The yield, protein recovery, and antioxidative properties of the locust-based protein can also be improved by UAE (Kingwascharapong et al., 2021). However, the alkalization treatment could lead to higher cooking loss because grasshopper protein possesses a higher proportion of hydrophobic groups that have poor water absorption. Combining alkalization with ultrasound negates this problem by decreasing the moisture content, thereby increasing the solid content and causing the changes in hydrophilicity or hydrophobicity of the protein (Cruz-López et al., 2022; Kingwascharapong et al., 2021). These findings illustrate that insect proteins, with appropriate treatments, can be a great low-cost alternative. However, further studies are needed to improve the sensorial experience of grasshopper proteins due to the detection of rancidity, undesirable seasoned and herbal smell, and taste of grasshopper protein in sausages.

PEF is an emerging technology utilizing short pulses (μs) of intense electrical current between two electrodes. These pulses create pores, known as electroporation, which can influence the extraction of protein or oil/fat extraction of the sample with limited undesirable change. For example, PEF was found to assist in the selective extraction of valuable intracellular components by disintegrating the molecular structure and cell permeabilization of the mealworms. PEF was found to enhance the selective extraction of lipids and dehydration of mealworm press cake while retaining the proteins and being more energy efficient (Shorstkii et al., 2022). PEF treatment in cricket enhanced the chitin appearance, fractionation of valuable compounds (proteins, fat, and chitin), extraction of protein (> 18%), oil binding (28.10%), emulsifying (64.88%), and antioxidant properties (58.20%) while preserving the chitin yield, water binding, and foaming capacity in cricket (Psarianos et al., 2022).

On the other hand, HHP is a nonthermal technology utilizing several thousand atmospheric pressures to inactivate microbiological contaminations and preserve the food components such as color, nutrition, and flavor. In a study by Boukil et al. (2022), soluble proteins from mealworms were shown to be unfolded/denatured, leading to increased surface hydrophobicity by exposing hidden hydrophobic amino acid residues to a more polar environment. The increased hydrophobicity was also seen during heating (H. Lee et al., 2019) and USE treatment (Rivero-Pino et al., 2020) of mealworm proteins. High-molecular-weight protein aggregates were also observed, which mainly consisted of hexamerin 2, α-amylase, myosin, and actin. Together, these phenomena can lead to a lower degree of protein hydrolysis (Dion-Poulin et al., 2020). Mealworms are rich in fibrous proteins (muscle), hemolymph proteins (hexamerins), and enzymes, causing them to be more susceptible to high pressure promoted by the presence of myosin and actin, which aid the formation of intermolecular S-S bonds (Boukil et al., 2022). To reduce the molecular weight and enhance the bioavailability of nutrients, further treatment using enzymatic hydrolysis might be needed (Urbina et al., 2021), which can lead to higher antioxidative capacity (Kim et al., 2021), solubility (Dion-Poulin et al., 2020), and reduced allergenicity (Boukil et al., 2020) of mealworm hydrolysates.

Interestingly, although mealworm proteins increased in solubility during HHP, cricket hydrolysates demonstrated otherwise, probably due to the different composition and profiles of peptides (Dion-Poulin et al., 2020). Bolat et al. (2021) claimed that pressurization alone was not able to increase the phenolic and antioxidant content of the mealworm oil, unlike in cricket oils. The authors further concluded that the antioxidants in crickets are easily affected by the increase in temperature during HHP. Similar authors also noted that HHP is beneficial to defat mealworms and cricket powder (Bolat et al., 2021). When HHP is used for the extraction of oils, mealworms showed higher extractability, up to 22.22%, compared to cricket oil extractability, which only went up to 18.09%. The composition of fatty acids was significantly affected by insect types and parameters used during HHP, demonstrating further flexibility in producing desired final products from insect oils (Ugur et al., 2021).

The use of SFE combined with dry fractionation on mealworms and crickets and its effect on carbohydrate portion (chitin), lipid, and protein was demonstrated by Sipponen et al. (2018). SFE can be a better alternative than solvent extraction by arresting lipid oxidation and protein conformational change (Ramos-Bueno et al., 2016). Lipid was almost completely removed during the process, except for a small amount of phospholipids with enrichment in PUFAs content. The yield was also shown to be comparable between conventional solvent extraction and SFE (Purschke et al., 2017; Sipponen et al., 2018), with SFE likely to be more rapid but cost-inefficient (Purschke et al., 2017). However, more research is needed to optimize yield and investigate the process of defatting using SFE (Choi et al., 2017). The crude proteins increased with a high amount of glutamic and aspartic acids. Consequently, fine-flavor intense and coarse chitin powder was obtained during specific milling procedures after the application of SFE and dry fractionation (Sipponen et al., 2018).

Conclusion

In conclusion, edible insects such as mealworms and locusts are potential sources of sustainable nutrients for food industrial applications. While the consumption of insects was initially deemed unfavorable, consumer sentiment has shifted toward a more positive awareness. The impact of cooking on nutritional values varies between different families of insects, more so with the different techniques or authors who performed them. As it moves down in the processing line, the effect of drying and extraction methods is becoming clearer, whereby nonthermal-related treatments such as freeze-drying tend to preserve nutritional factors while heat improves the Maillard-related antioxidative capacities. The use of emerging green technologies such as UAE, HHP, SFE, and others may produce better nutritional characteristics while being environmentally sustainable, but their applications might be limited due to many factors such as cost, complexity, and impact on nutritional quality. Therefore, it is crucial to consider a combination of conventional and new processing methods to optimize the production of edible insect products with a preferred nutrition outcome. For future consideration, the impact of processing can be further evaluated using in vivo studies and on the minor nutrients such as vitamins and phenolic compounds.

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Data Availability The authors declare that the data supporting the findings of this study are available within the article.

Declarations

Conflict of Interest The authors declare no competing interests.

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