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Review Article

A Review of Pre-treatments, Drying Methods, and Processing of High-protein Insect Products

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ABSTRACT

Pre-treatment and drying techniques are vital in producing high-quality insect products. Pre-treatments ensure that moisture and undesirable elements, such as gut contents and microorganisms, are removed while preserving the nutritional values of insects. Drying techniques are also crucial to reducing moisture levels, halting bacterial and fungal growth, and extending product shelf life. Several studies have reported on pre-treatment and oven, freeze, sun, smoke, fluidised bed, vacuum, and microwave drying. High-quality insect products, including powders and flakes, have been successfully produced through pre-treatment and drying technique combinations. Generally, insect pre-treatment and drying approaches depend upon the intended usage and desired attributes of the products. This study reviewed pre-treatment and drying methods for insect products to enhance the effectiveness of the insect-based food sector, and their potential applications as sustainable options for both animal feed and human food, while briefly discussing insects as a solution to global protein shortages, their nutritional benefits and associated health risks.

Keywords: Drying, feed, insects, pre-treatment, processing

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INTRODUCTION

Approximately 80% of known species worldwide are insects, with an estimated 5.5 million species having been identified (Stork, 2018). Their abundance renders

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insects an excellent alternative protein source. Insects are also a sustainable protein option for the growing global population as they offer significant environmental benefits, such as rearing on organic waste, requiring minimal land and water, and producing low levels of greenhouse gases (Rumpold & Schlüter, 2015).

Insects are rich in essential nutrients, including protein, iron, and calcium, providing additional nutrients to support human growth and development (Nowakowski et al., 2021). The rapid reproduction rates and minimal space requirements of insects offer a viable solution to future food security issues and further enhance their reliability as a protein source (De Matos et al., 2024; Mohamad et al., 2021). Consequently, insects are being processed into various food items such as protein bars, powders, and snacks, to cater for the demands of health-conscious consumers (Melgar-Lalanne et al., 2019).

In rural areas where traditional agriculture is not feasible, processing insects creates job opportunities, thereby reducing poverty and improving livelihoods (Rumpold & Schlüter, 2013; Van Huis et al., 2013). The initiative also supports local economies by fostering small-scale enterprises and promoting innovative food solutions, developing communities, and increasing food security and resilience against economic fluctuations (Food and Agriculture Organisation of the United Nations [FAO], 2013).

Insects are pre-treated before undergoing processing. Commonly, insect pre-treatments include blanching and freezing (Ciurzyńska et al., 2021; Rumpold & Schlüter, 2013; Van Huis et al., 2013). Nevertheless, the processing stages, which might involve drying, could damage and/or modify the vitamins, minerals, antioxidants, pigments, and other bioactive chemicals that provide various health advantages offered by insects (Ssepuuya et al., 2020). Undesired colour changes on the final products have also been reported (Ssepuuya et al., 2020). Various pre-treatments have been applied to reduce nutrient losses and enhance the nutritional and sensory values of dried insects (Calín-Sánchez et al., 2020; Yegrem & Ababele, 2022).

Currently, processing insect techniques rely on mechanical (grinding, pressing, and milling), thermal treatments (blanching, boiling, drying, cooling, freezing, and freeze drying), and fractionation processes (extraction, purification, separation, and centrifugation) (Parniakov et al., 2021). Drying is defined as vaporising and eliminating moisture from a substance and its surfaces, typically with the assistance of a carrier gas travelling through or over the material (Keey, 1992). The technique is the oldest, most popular, and most practical method of insect processing (Parniakov et al., 2021).

Drying insect products offers several advantages. The treatment improves preservation by reducing microbial growth and spoilage-enzyme activity in insects (Morgan et al., 2006). Nonetheless, the types of drying methods employed affect the quality of the final product (Bogusz et al., 2023). Drying is the most preferred approach, even though the procedure affects the colour, density, dimension, hardness, and nutritional values of the insects (Purschke et al., 2018). Common drying methods applied during insect processing include sun, oven, freeze, and microwave drying (Van Huis & Tomberlin, 2017). Solar, fluidised bed, and vacuum drying and sand roasting have also been documented (Parniakov et al., 2021).

Insect pre-treatment and drying process optimisation are necessary to enhance and preserve the nutritional values of the resultant products. Moreover, information on insect pre-treatment and drying procedures is critical to producing insects as feed and food. This review aims to summarise available insect pre-treatment, drying techniques and the associated drying parameters based on the region or countries that primarily implement modern and traditional insect pre-treatment and drying methods. All nations could benefit from the application of various drying procedures, particularly in regions where insect processing equipment is not easily accessible. Furthermore, the present review might offer broader research paths, including pre-treatment and drying methods, for industrial-scale insect processing applications.

METHODOLOGY

In this review, a comprehensive literature search was conducted through online databases, including PubMed, ScienceDirect, and Google Scholar. The search criteria employed were insect pre-treatment, blanching, freezing, pulsed electric field applications, insect drying and sun-drying methods, and insect-based products. Manual searches of key publications were also performed by reviewing the reference lists of relevant papers.

The articles reviewed were selected based on their relevance to the objectives of the study. Peer-reviewed journal-published empirical research focusing on drying methods, insect pre-treatment, and products derived from insects was considered for inclusion. Quantitative and qualitative articles were also eligible. Nonetheless, only scientific reports, conference proceedings, books, abstracts, and theses written in English and Malay were included. Publications not providing information on insects, published in languages other than English or Malay, possessed insufficient data descriptions (such as incomplete pre-treatment and drying method descriptions), and did not align with the review objectives, were excluded.

The present review extracted data from the selected articles, including study characteristics (such as author, year, and study design), sample details (including types of samples), intervention specifics (such as type of pre-treatment and, drying method), outcome measures, and principal findings related to the quality and production of insect-based products. Subsequently, the information was categorised into major topics and subtopics to allow a comprehensive assessment of the influences of pre-treatment and drying interventions on the quality of the final product. A total of 108 articles published between 2000 and June 2024 were selected based on the inclusion criteria previously mentioned. Bibliographies from the selected articles also led to the identification of other relevant studies.

RESULTS AND DISCUSSIONS

Insects as a Solution to Global Protein Shortages

The global demand for protein is projected to surge by 20% by 2050 as the population surpasses nine billion, particularly in emerging nations where economic growth drives increased consumption of animal protein (Smith et al., 2024). Insects offer a promising, sustainable alternative protein source that could alleviate the environmental and ethical impacts associated with conventional livestock production, addressing global protein shortages through reduced greenhouse gas emissions, minimal land and water use, preservation of biodiversity, and improved energy efficiency, all while considering animal welfare implications (FAO, 2014).

Greenhouse gas emissions per kilogram of insect protein were lower than those for beef and pork but higher than those for chicken and fish (van Huis et al., 2013). Similar findings were reported by van Loon et al. (2018), showing that greenhouse gas emissions per kilogram of mealworm protein were lower than those for beef and pork but higher than those for chicken and fish. Animal welfare is another element that is becoming more significant. In comparison to conventional livestock production, insect farming could provide a more compassionate method (Smetana et al., 2023). In contrast to larger animals, insects may be raised in smaller settings that better suit their natural preferences, resulting in less stress and easier access to food (van Huis et al., 2013). This change not only addresses ethical concerns related to intensive animal farming but also meets consumer demand for more humane methods of food production.

Insect protein is gaining recognition as a sustainable alternative to traditional protein sources. Insects are exceptionally high in protein, fat, and micronutrients (Rumpold & Schlüter, 2013). Edible insects have a greater protein concentration than plant protein sources, including wheat, soybeans, and lentils, ranging from 35% to 60% dry weight or 10% to 25% fresh weight on average (Melo et al., 2011; Schlüter et al., 2017). At the upper range, insects provide more protein than even meat and chicken eggs (Mlcek et al., 2014). Orthopteran edible insects, such as locusts, grasshoppers, and crickets, are very high in protein (Rumpold & Schlüter, 2013). However, because insects have an extremely rigid exoskeleton, their protein digestibility varies greatly (van Huis, 2016). High chitin content exoskeletons are particularly challenging to digest (Schlüter et al., 2017). Muzzarelli et al. (2012) indicate that the digestibility of chitin in humans remains uncertain. However, the exoskeleton can be effectively removed during processing (Rumpold & Schlüter, 2013). As summarised in Figure 1, various insect processing methods help address these problems.

Figure 1 outlines the methods of processing insects, which are divided into several steps. The first phase involves harvesting the insects. Subsequent stages involve subjecting the insects to pre-treatment processes, drying, and preparing them for commercialisation. The details of each phase are discussed in the following sections.

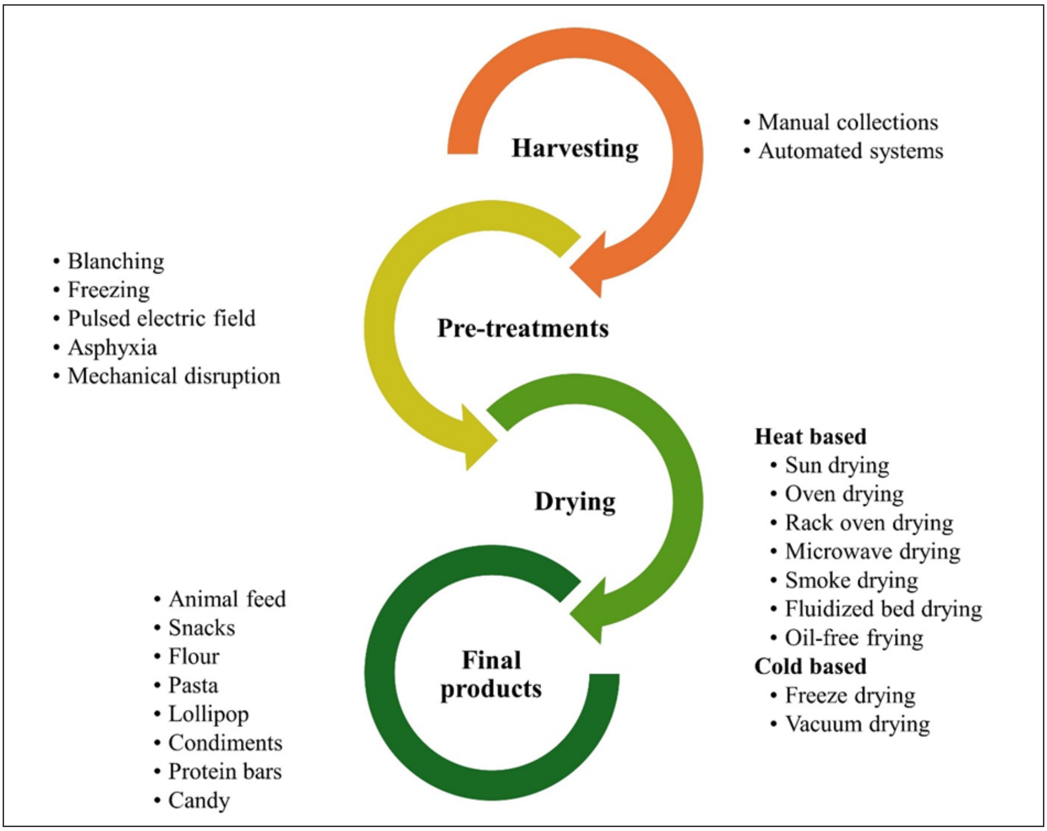

Figure 1. Summary of insect processing steps

Harvesting Process

Based on Figure 1, the initial phase of insect processing is harvesting the insects. The step is fundamental to the production chain. Harvesting is typically performed manually at small-scale production levels (Cerritos & Cano-Santana, 2008). Nevertheless, automation and industrial-scale production have become indispensable due to increasing demands for insect-based products (Berggren et al., 2018).

Automated insect harvesting systems include advanced technologies (Droukas et al., 2022). The innovations enhance productivity by allowing continuous and efficient insect collection (Sindermann et al., 2021). The approaches also facilitate production scalability without significantly increasing labour costs (Sindermann et al., 2021). Furthermore, insect farming automation boosts production volumes and ensures consistent product quality by minimising handling stress and reducing contamination risks during harvesting (Ojha et al., 2021). Advances in the industry also allowed the integration of automation into insect harvesting processes, hence driving innovation, efficiency, and sustainability in the agriculture and biotechnology sectors (Rumpold & Schlüter, 2013).

Pre-treatment Phase

Harvested insects are pre-treated (Alles et al., 2020). Pre-treatment, or the insect-killing method, reduces microbial contamination and facilitates long-term storage of the final products (Adamek et al., 2018). Commonly employed insect pre-treatment procedures include blanching, freezing, and pulsed electric fields (Table 1). The pre-treatment methods extend the shelf life of insect-based products and maintain their nutritional contents and quality attributes, supporting the growth of the insect food industry (Larouche et al., 2019).

Table 1
Summarisation of pre-treatment methods for insect

Insect species	Pre-treatment	Condition and Results	References
Hermetia illucens larvae	Blanching	Condition: 100 °C, 40 seconds. • Reduced protein content, potentially lowering overall nutritional content.	Zhen et al. (2020)
		• Reduces protein browning caused by phenol oxidase, improves protein extractability, and increases susceptibility to enzymatic digestion.	Leni et al. (2019)
Tenebrio molitor larvae	Blanching	Condition: 60 °C, 5 minutes. • Reduces microbial loads and stops the browning effect.	Mancini et al. (2019)
		Condition: 100 °C, 40 seconds. • Small decrease in protein and ash content. • Increase in water content.	Lenaerts et al. (2018)
		• Significant log reductions in Enterobacteriaceae, lactic acid bacteria, yeasts, moulds, and psychrotrophs. • Aerobic endospores are not affected.	Vandeweyer et al. (2017)
Hermetia illucens larvae	Blanching	Condition: 100 °C, 40 seconds. • Minimises lipid oxidation. • Reduces microbial contamination. • Initiates dehydration.	Larouche et al. (2019)
Polyrhachis vicina Roger	Freezing + Sun drying	Condition: -20 °C, 24 hours. • The sun-dried black ant had 28 organic components. • Combining freezing and sun drying speeds up lipid oxidation and hydrolytic rancidity.	Li et al. (2009)

Table 1 *(continue)*

Insect species	Pre-treatment	Condition and Results	References
Hermetia illucens larvae	Pulsed electric field	Condition: Monopolar pulses with an interval of 0.5 s (2 Hz), pulse duration 40 ms, specific energy intake of 10, 15, and 20 kJ/kg. • Reduces drying time and oil droplet size. • Enhances oil extraction from insects within specific power ranges.	Alles et al. (2020)
		Condition: Electric field strength: E= 1 to 3 kV/cm, specific energy: 1 to 20 kJ/kg, time: 3 h. • Optimal drying temperature is between 81-84°C and 11.2-13.1 kJ/kg of specific PEF energy input.	Shorstkii et al. (2020)
Tenebrio molitor larvae	Pulsed electric field	Condition: Peak voltage up to 30 kV and provided monopolar, rectangular pulses with a duration of 40 µs and frequency of 2 Hz. • Improved infrared drying kinetics. • Reduced browning in T. molitor infrared dried larvae biomass. • Improved microbial quality compared to untreated samples.	Bogusz et al. (2022)
Acheta domesticus	Pulsed electric field	Condition: Treatments were carried out at 1.5 kV/cm. The nominal pulse width and the frequency were kept constant at 15 µs and 20 Hz, respectively, with energy input between 4.9 and 49.1 kJ/kg. • Increased protein and fat yield. • Improved techno-functional properties. • Positively impacted chitin structure, increasing oil binding and emulsifying capacity.	Psarianos et al. (2022)
Drosophila melanogaster larvae	Asphyxia	Condition: The larvae were exposed to 100% CO_2 in a sealed petri dish. • Lethal for the larvae in 30 minutes.	Badre et al. (2005)
Adult grasshopper species	Asphyxia	Condition: The samples were placed in nitrogen gas-bubbled spring water (completely deoxygenated water). • Adult grasshopper species may live between 7.5 to 22 hours • The nymph of the same species can only survive between 3 to 13 hours.	Brust et al. (2007)
Musca domestica	Mechanical disruption	Condition: Grinding. • Most environmentally friendly technique.	Erens et al. (2012)

Blanching and freezing are the most utilised insect pre-treatment procedures (Mutungi et al., 2019). Blanching involves treating food with heat, such as steam or boiling water (Karim et al., 2023). The time and temperature parameters employed during the procedure depend upon the type of raw material and the final processing method (Lee, 1958). Typically, blanching is conducted at 60°C to 100°C for a brief period (between 40 s and 5 min), depending on the insects being processed (Hernández-Álvarez et al., 2021). Nevertheless, insects should be cooled rapidly after blanching to avoid the growth of surviving yeast and bacteria (Karim et al., 2023).

Blanching inactivates enzymes and microorganisms in insects, preventing undesirable deterioration in flavour, odour, nutrient content, pH, and colour (Mancini et al., 2019). *Tenebrio molitor* larvae exhibited a significantly diminished microbial load and halted browning, evidencing enzymatic inhibition following blanching at 60 °C for 5 min (Mancini et al., 2019). Similarly, Saucier et al. (2020) reported that blanching *Hermetia illucens* larvae at 100 °C for 40 s reduced their microbial load from 3.21 to 4.83 log in the dry product. In another study, Vandeweyer et al. (2017) investigated the effects of rapid blanching (10 to 40 s) followed by chilled storage or commercial microwave-drying on the microbial load in mealworms. The report revealed that blanching (with or without microwave-drying) destroyed vegetative cells but not bacterial spores. The blanched mealworms could be kept in refrigerators for six days without significant microbial development.

Blanching has several effects on insects, including microbial load reduction, thus lowering microbiological risks in the final products (Kouřimská & Adámková, 2016). Blanching also diminishes insect lipid oxidation primarily through enzyme deactivation and oxygen availability reduction (Belluco et al., 2013). Furthermore, blanching aids in preserving the natural colour of insects by inactivating polyphenol oxidase and peroxidase, which are responsible for the browning process, preventing discolouration (Yi et al., 2013). Blanching also softens exoskeletons, increasing the palatability of the insects (Rumpold & Schlüter, 2013).

During freezing, insects are exposed to extremely low temperatures, typically below −20°C (Hernández-Álvarez et al., 2021). The procedure ultimately kills or inactivates the insects due to tissue damage or basic function alterations (Lee, 1991). Nonetheless, the success of the treatment depends on the duration and freezing depth, as different insects possess differing degrees of tolerance to freezing temperatures. Low freezing temperatures lead to considerable ice crystal formations, resulting in significant water loss and inactivation of beneficial microorganisms, yielding low-quality end products (Larouche et al., 2019). Larouche et al. (2019) also reported that freezing *H. illucens* larvae at −20°C only reduced *Pseudomonas* spp. counts, requiring additional decontamination steps.

Low temperatures during freezing inhibit the growth of microorganisms already present in the environment and slow biochemical reactions that occur even after the insects are killed (Ščetar & Galić, 2017). Nevertheless, freezing does not lessen microbial load or deactivate several hydrolytic enzymes responsible for quality degradation, which might lead to unfavourable flavour, colour, and textural changes in the insects (Montevecchi et al., 2020). In *Alphitobius diaperinus*, freezing negatively affected protein solubility, forming fat-protein aggregates that intensified browning before and after processing and raised phenol-oxidase activities during storage (Wessels et al., 2020).

Pulsed electric field (PEF) pre-treatment is a novel approach that temporarily permeabilises insect cell membranes with high-voltage pulses (Shorstkii et al., 2020). The process results in small pores in the cell membranes, leading to reversible or irreversible electroporation (Alles et al., 2020). The pre-treatment was successfully applied to *H. illucens* and *T. molitor* larvae and *Acheta domesticus* (Alles et al., 2020; Bogusz et al., 2022; Shorstkii et al., 2020).

According to Bogusz et al. (2022), *H. illucens* and *T. molitor* larvae biomass infrared drying kinetics improved following a PEF treatment at 5 kJ/kg, which modified some water binding capabilities. The treatment also increased browning in dried *H. illucens* biomass but decreased dried *T. molitor* biomass during infrared drying (Bogusz et al., 2022). Dried insects subjected to PEF also exhibited superior microbiological quality compared to untreated samples (Bogusz et al., 2022).

Psarianos et al. (2022) demonstrated that the protein and fat yields in *A. domesticus* treated with PEF increased by 18.62% and 41.75%, respectively. The article also noted that PEF enhanced the oil-binding and emulsifying abilities of the organism by approximately 40% and 70%, respectively, thereby improving techno-functional qualities. Furthermore, the chitin structure of the *A. domesticus* (10 g/100 g d.w.) was favourably influenced by PEF treatment.

Mahnič-Kalamiza et al. (2014) reported that PEF facilitated the release of intracellular components by creating pores in cell membranes. The phenomenon improved lipid, protein, and other crucial component extractions from insects. The pre-treatment procedure also reduced insect microbial loads, enhancing the safety and shelf life of insect-based products (Barba et al., 2015). PEF could also increase insect drying efficiency by enhancing their permeability and shortening the drying time (Alles et al., 2020). Moreover, cell membrane disruption during the pre-treatment reduces lipid oxidation (Barba et al., 2015).

Asphyxiation involves exposing insects to an environment with low oxygen levels or full oxygen deprivation, which leads to suffocation and eventually death. Carbon dioxide (CO_2) is commonly employed for anaesthetising invertebrates, with exposure times ranging between 3 min and 60 min, depending on the insect species (Erens et al., 2012). A CO_2 concentration exceeding 40% causes neuron depolarisation without altering conductance, immobilising insects (Clark & Eaton, 1983). Nevertheless, prolonged exposure could be fatal due to the lowering of haemolymph pH and insect dehydration initiation by promoting spiracle opening (Wong-Corral et al., 2013).

Saturating the air with nitrogen (N_2) is another method of asphyxiation, which necessitates under 3% oxygen content (Hashem et al., 2014). Vacuum packing and drowning are also applicable since large-scale air saturation might be challenging. Insect resistance to hypoxia varies according to species and developmental stages (Fernandez-Cassi et al., 2019). For instance, a study found that *Ephestia cautella* (Lepidoptera) larvae mortality rate exposed to 98% N_2 considerably varied, typically occurring within 96 h to 144 h, which was one to two days longer than the time recorded by larvae in aerobic environments of 60% CO_2 (Hashem et al., 2014).

The grinding pre-treatment entails mechanically reducing insects to tiny particles or powder with grinding equipment. Halloran et al. (2018) indicated that grinding breaks down insect structural integrity, reducing them into smaller particles or powder, allowing further processing and integration into food products. The procedure ensures particle size homogeneity, necessary for producing insect-based goods with consistent texture, flavour, and appearance (Rumpold & Schlüter, 2013). Nonetheless, grinding fresh insects has resulted in browning in numerous insects due to enzymatic and non-enzymatic reactions with polyphenols, which could reduce product quality (Janssen et al., 2017; Janssen et al., 2019; Yi et al., 2013). Accordingly, grinding should be conducted after stabilising the product.

Drying Methods

The techniques for drying insects are categorised into heat- and cold-based methods (Melgar-Lalanne et al., 2019). Heat-based approaches include sun, oven, microwave, smoke, and fluidised bed drying. On the other hand, cold-based approaches comprise freeze and vacuum drying. The information on the techniques is summarised in Table 2.

Generally, heat-based drying methods are preferred over their cold-based counterparts (Hernández-Álvarez et al., 2021). According to Omari et al. (2018), heat-based techniques are rapid and effective. Moreover, hot air convection and infrared radiation allow rapid drying (Mujumdar, 2006; Sharma et al., 2005). Heat drying is also more economical than energy-intensive methods, such as freeze drying (Novak & Lewicki, 2004). Moreover, heat-based drying is simple to manage, offering better drying process regulation than other approaches, including temperature adjustments required by different materials (Stramarkou et al., 2021).

Every strategy has different drawbacks and advantages. For instance, heat-based drying techniques lower product quality by causing shrinkage, warping, or cracking (Andharia et al., 2023). The process involves heating a material continuously, leading to excessive energy consumption and energy expenditure. Moreover, heat-based drying might pose safety hazards, such as fire threats, if performed inappropriately.

Table 2
Summarisation of drying methods for insect

Insect species	Common name	Drying method and condition	Main findings	References
Rhynchophorus phoenicis	Palm weevil	Solar: 5 days Oven: 50 °C (48 hours) Smoke: 6 hours	The best preservation technique for lipids was discovered to be smoking.	Tiencheu et al. (2012)
Sternocera orissa	Giant jewel beetle	Oven: 66 °C /24 hours Freeze: -55 °C /24 hours Frying pan: 130-cm diameter, 50-mL tap water. Fried without cooking oil.	Oven drying and cooking methods improved the proximate chemical composition.	Shadung et al. (2012)
Imbrasia epimethea	African moth	Oven: 80 °C /8 hours Solar: 3 days	Both drying methods showed a slight reduction in monounsaturated fatty acids.	Lautenschläger et al. (2017)
Ruspolia differens	Longhorn grasshopper	Freeze dry: Phase (1) −50 °C/0.40 bars/48 hours Phase (2) −55 °C/0.021 bars/48 hours Oven: 60 °C /24 hours	Both drying methods produced the same nutritional quality.	Fombong et al. (2017)
Tenebrio molitor	Mealworm larvae	Microwave assisted drying: 8, 10, 13, 16, 20 min/ 2 kw	Drying for 16 or 20 minutes produced average water activity of 0.16 and 0.23, which is required to completely stop microbial development.	Vandeweyer et al. (2017)
Polyrhachis vicina Roger	Black ant	Sun: 20–35 °C	Sun drying speeds up lipid oxidation and hydrolytic rancidity.	Li et al. (2009)
Musca domestica	Housefly larvae	Oven and sun dry	Oven drying yields higher protein larvae while sun drying yields higher fat content.	Aniebo and Owen (2010)
Hermetia illucens	Black soldier fly larvae	Oven: 60 °C Microwave drying: 500 W/15 min	Conventional and microwave-dried larvae have an essential amino acid to total amino acid ratio greater than 40%.	Huang et al. (2019)

Table 2 *(continue)*

Insect species	Common name	Drying method and condition	Main findings	References
Tenebrio molitor	Mealworm larvae	Hot air: 60 °C/7 hours and 24 hours, 80 °C/7 hours and 24 hours. Freeze-dry: 0.2 mbar/48 hours. Fluidised bed: bed temperature 60 °C, air outlet temperature 55 °C, differential pressure bed 15 bar, differential pressure filter -1.3 bar, air flow 500 $m^3 h^{-1}$/2 hours.	Due to browning reactions and tissue collapsing, drying at high temperatures resulted in considerable darkening and shrinkage.	Purschke et al. (2018)
Tenebrio molitor	Mealworm	Rack oven: 120 °C /1 hour/ ventilation stage 2. Freeze dry: -50 °C /24 hours Vacuum: vacuum oven 60 °C/ 24 hours	The mealworm powder with the best solubility was obtained via vacuum drying.	Kröncke et al. (2019)

Sun drying is a classic method of drying, which has been applied to vegetables, meats, seafood, fruits, and insects for a long time (Malakar et al., 2022). Nevertheless, direct sunlight drying necessitates a considerable open space, is significantly dependent on daylight, exposes items to insects, birds, and rodents, and is prone to contamination from foreign contaminants, including litter and dust (Agbede et al., 2023). Nevertheless, Yisa et al. (2022) suggested sun drying as a cost-efficient and effective alternative to oven and freeze drying for preserving edible insects, such as grasshoppers (*Ruspolia differens*), crickets (*Gryllus bimaculatus*), and caterpillars (*Bunea alcinoe*).

Prolonged sun drying might lead to heat-sensitive vitamin degradation, such as vitamins C and B (Halloran et al., 2018). According to Nguyen and Nguyen (2015), sun drying might render insect lipids vulnerable to oxidation, which could result in lipid-soluble vitamin breakdowns and unpleasant smell and taste developments. Water-soluble substances leaching, such as several B vitamins and minerals, might also occur from extended exposure to heat and sunshine during drying, specifically if the insects are not properly shielded (Halloran et al., 2018).

Oven drying is the most employed method due to its cost-effectiveness and adaptability to industrial operations (Table 2). Oven drying is a controlled dehydration process that utilises heat to remove moisture from objects or materials. Although various systems, including vacuums and rotating ovens, are applicable, their impacts on the products might differ (Kröncke et al., 2018). Employing high temperatures during oven drying also could have detrimental effects on several functional qualities of the insects when turned into ingredients, particularly proteins (Azagoh et al., 2016; Kröncke et al., 2019).

Low temperatures are preferable in protein solubility preservation and Maillard reaction, shrinkage, and tissue collapse reduction (Kröncke et al., 2018; Melis et al., 2018; Purschke et al., 2018). Generally, temperatures between 50°C and 120°C are applied from 1 h to a few days (Kröncke et al., 2018; Melis et al., 2018; Purschke et al., 2018). Azzollini et al. (2016) found that the optimum drying temperature that minimised negative impacts and shortened the drying time was 60°C. In another study, Tiencheu et al. (2012) reported that oven-dried *Rhynchophorus phoenicis* exhibited raised peroxide values, particularly when boiled before being dehydrated. Conversely, oven-dried *Sternocera orissa* significantly recorded increased essential and non-essential amino acids (Shadung et al., 2012).

Microwave drying relies on the interactions between the electromagnetic radiation in the microwave frequency range and the moisture content of the material being dried. Primarily, microwave drying is more rapid than oven and freeze drying regarding drying insects (Kröncke et al., 2019). Bawa et al. (2020) noted that microwave drying was considered the most suitable for *A. domesticus* (crickets), considering their notable mineral element levels. The process improved colour parameters and had less microbiological load than the oven-dried samples. Nonetheless, the approach might denature the proteins and affect the functional qualities of the resulting components, similar to oven drying (Shorstkii et al., 2020).

Microwave drying requires 10 to 15 min, subject to microwave parameters, to completely dry insects (Lenaerts et al., 2018). Although the technique yields inflated, complete, and dried larvae, it permits browning in *T. molitor* larvae (Lenaerts et al., 2018). Furthermore, microwave-dried mealworm protein solubility documented a 40% reduction (Kröncke et al., 2018). Compared to oven-drying at 60 °C, microwave drying led to protein polymerisation in BSF larvae, which lowered the digestible amino acid score and digestibility, producing a powder with larger particle sizes (Huang et al., 2019).

Smoke drying is another food preservation technique which utilises heat and smoke. According to Ledesma et al. (2017), the method frequently preserves meat, fish, and other foods across civilisations globally. The raw products are exposed to smoke from wood pyrolysis, and the procedure is commonly coupled with salting. The entire process integrates heating, drying, salting, and smoking in a smoking chamber (Hernández-Álvarez et al., 2021). Nevertheless, the procedure could adversely affect the flavour of the final products (Hernández-Álvarez et al., 2021).

Smoke-dried insects are less documented than other drying processes (Table 2). Tiencheu et al. (2012) investigated the method on *Rhynchophorus phoenicis*, where a 6-h smoke drying procedure resulted in high-quality products. Nonetheless, smoke drying is less preferred due to health hazards from the smoke, which might contain carcinogenic compounds (Essumang et al., 2013). Studies have also reported that smoke-dried products could have polycyclic aromatic hydrocarbons linked to increased cancer risks (Alexander et al., 2010).

A fluidised or fluid bed dryer is a type of machinery commonly utilised in the chemical, food, and pharmaceutical industries to dry heat-sensitive materials that tend to clump together rapidly (Bhakar, 2023). The technique was designed to reduce the moisture content of wet flakes, granules, and powders. During fluidised bed drying, heated air is introduced under high pressure into a perforated bed containing wet solid particles. Subsequently, the damp solids are lifted from the bottom and suspended in a fluidised state, floating within an airstream. Heat is transferred through the direct contact between the wet material and the hot gases. The drying gases transport the vapourised liquid. Kröncke et al. (2019) extensively studied the approach utilising *T. molitor* larvae. The article reported that the fluidised bed-dried mealworms exhibited lower water solubility (19.25% ± 0.21%) than their freeze-dried counterparts (40.65% ± 0.21%).

Fluidised bed drying offers comparatively lower drying times and requires larger-scale continuous manufacturing than vacuum drying and freeze drying (Bayrock et al., 1997). Nevertheless, fluidised bed drying might lead to protein denaturation at high temperatures, potentially affecting their functional qualities when utilised as ingredients (Kröncke et al., 2019). Although fluidised bed drying at 130°C for 110 min could slightly increase lipid oxidation, the procedure might also cause browning (Kröncke et al., 2018).

Although the heat-based drying method is commonly preferred, certain insect species require cold-based drying approaches (Table 2). Cold-based drying procedures employ dry and cold air to remove moisture from a material or item. After reaching the necessary moisture content, a material dries when subjected to circulating low-humidity air (Kilic, 2009). The preservation technique is frequently employed in industrial settings as it offers a less harmful alternative to heat drying (Kilic, 2009). The strategy is commonly applied in food processing, electronics production, and the storage of sensitive chemicals. Examples of cold-based drying methods include freeze-drying and vacuum drying.

Cold-based drying processes yield fewer risks of product damage or quality degradation (Kilic, 2009). Cold air drying also contributes to reduced product oxidation, whereas high temperatures might result in oxidation and spoiling, which could affect the colour and flavour of the products (Van Loey et al., 2005). Furthermore, drying at a low temperature preserves the nutritious contents of the products (Shonte et al., 2020).

Although cold air drying provides numerous food preservation advantages, the technique has some drawbacks. For instance, cold air requires a longer period to dry compared to hot air. Furthermore, cold air drying requires large spaces for air circulation. Several products benefit from cold air drying, while materials containing considerable water content might necessitate heat or a specific drying atmosphere. Moreover, inappropriately managed cold-dried materials might increase humidity and increase mould formation risks (Erkmen & Bozoglu, 2016).

Table 2 shows that freeze drying is the most utilised cold-based drying method. The technique is sometimes referred to as lyophilisation, which eliminates moisture from a product without affecting its composition or characteristics. For instance, Yi et al. (2013) documented that the essential amino acid levels of freeze-dried *A. domesticus*, *A. diaperinus*, *T. molitor*, *Zophobas morio*, and *Blaptica dubia* were equivalent to those in soybean proteins. In freeze drying, a material is frozen before it is placed in a vacuum atmosphere to sublimate the frozen water (Kröncke et al., 2019). Biological samples and perishable products, including fruits, vegetables, meats, and insects, are frequently preserved through freeze-drying (Kröncke et al., 2019).

Freeze drying is one of the best drying processes for retaining insect colour since it does not induce the Maillard reaction, hence yielding the whitest powder (Lenaerts et al., 2018). Furthermore, freeze-dried larvae appear inflated rather than shrunken, which might increase consumers' acceptance (Larouche et al., 2019). Nevertheless, the technique is expensive, with a minimum of 24 h to 53 h required to completely dry insects (Kröncke et al., 2018; Lenaerts et al., 2018). The approach also reduced protein solubility by 10% (Kröncke et al., 2018). Although freeze-drying causes lipid oxidation, leading to significant quality loss, blanching decreases the effects by half when applied before freeze-drying (Kröncke et al., 2018; Lenaerts et al., 2018).

Establishing a low-pressure atmosphere to remove moisture from a product is the procedure involved in vacuum drying (Kröncke et al., 2019). A material is placed in a vacuum chamber, which removes the pressure, and evaporation eliminates moisture. Vacuum drying requires less time and energy, considering the lower temperature and swifter pace of water evaporating in a vacuum than in normal air circumstances (Earle, 1969). Seho et al. (2021) demonstrated that blanching and vacuum drying *T. molitor* larvae reduced over 5 log *Escherichia coli* load and optimally preserved the brightness of the larvae.

Vacuum drying preserves heat-sensitive chemicals at lower temperatures than fluidised bed and oven drying. Nevertheless, the technique is time-consuming and possesses limited applicability on a broad scale due to the time required to dry insects. Vacuum drying employs low temperatures and pressures to reduce lipid oxidation and browning, retaining insect quality (Rumpold & Schlüter, 2013). Furthermore, vacuum drying has been proven to preserve the protein content and overall nutritional value of edible insects better than conventional drying techniques (Ssepuuya et al., 2017).

Insect Processing and the Resultant Products

According to Melgar-Lalanne et al. (2019), insects are gaining attention as prospective dietary components for sports dietary supplements, such as protein concentrates or isolates, flours, energy bars, protein shakes, and hydrolysates, due to their notable protein contents and well-balanced amino acid profile. Mealworms were the first species to be authorised as food following the risk assessments on insects by the European Food Safety Authority (EFSA) in 2018 (Turck et al., 2021). Consequently, edible insects have been sold as flours, heat-dried larvae, pupae, and dried and powdered adult insects (Table 3). Edible insects are also available in various forms, including bulk goods in powder and flour forms, candy, chocolate-covered snacks, and liquor infusions (Melgar-Lalanne et al., 2019).

Table 3
Insect processing and products according to the countries

Insect species	Drying method	Product	Countries	Sources
Tenebrio molitor	Freeze dried	Feed	United States	https://www.etsy.com/market/freeze_dried_mealworm?ref=lp_queries_internal_bottom-8
Acheta domesticus	Roasting	Snacks	Malaysia	https://www.ento.my/collections/catalog
Hermetia illucens larvae	Microwave dried	Feed	Malaysia	https://biovae.com.my/shop/biovaegrubs-dried-bsfl/
Haplopelma albostriatum	Oven drying	Snacks	Thailand	https://www.thailandunique.com/canned-edible-tarantula-spider
Platylomia Radah	Microwave dried	Snacks	Thailand	https://www.thailandunique.com/edible-insects-bugs/edible-cicadas-for-sale
Bombyx mori pupae	Sun dried	Feed	China	https://www.alibaba.com/product-detail/Sun-Dried-Silkworm-Pupae_234965973.html?spm=a2700.7724857.0.0.12363cfbqzy23X
Tenebrio molitor larvae, *Acheta domesticus*, *Locusta migratoria*	Microwave dried	Lollipops	United Kingdom	https://www.crunchycritters.com/shop/buy-edible-insects/lollipops/lollipops-4-x-30g/
Alphitobius diaperinus	Freeze dried	Lollipops	United Kingdom	https://www.crunchycritters.com/shop/buy-edible-insects/lollipops/lollipops-4-x-30g/
Bombyx mori pupae	Oven dried	Candy	Thailand	https://www.thailandunique.com/chocolate-covered-insects/chocolate-covered-silkworms
Zophobas morio	Oven dried	Candy	Thailand	https://www.thailandunique.com/chocchoco-covered-insects/white-chocolate-superworms
Acheta domesticus	Freeze dried	Protein bars	Singapore	https://altimatenutrition.com/products/chocolate-banana-cricket-protein-bar

In the European Union, only four insect species have been approved as food: (1) dried *T. molitor* larvae, (2) *Locusta migratoria* (frozen, dried, and in powder form), (3) *A. domesticus* (frozen, dried, powder form, and partially defatted powder), and (4) *A. diaperinus* larvae (frozen, dried, and paste and powder forms) (Parniakov et al., 2021). Meanwhile, approximately 200 insect species are consumed in Thailand (Mongkolvai et al., 2009). The insects are prepared in creative ways, such as curries, dipping (combined with chilli paste), and salted, in addition to the standard roasting, frying, and steaming (Halloran et al., 2015; Raheem et al., 2018). Nonetheless, consumption is localised. For instance, although crickets are a northeastern Thailand speciality, they are rare in Bangkok restaurants as they are perceived as a rural poverty sign (Halloran et al., 2016).

Only the Borneo regions of Malaysia practice entomophagy. Durst et al. (2010) documented that *Rhynchophorus ferrugineus* larvae are valued for their significant protein content and consumed stir-fried or roasted in Borneo. Various species of grasshoppers, such as pointed-nose, short-horned, leaf-like, and *Valanga* sp., are also consumed in that region. Typically, the grasshoppers are boiled, lightly seasoned, and simmered until dry, and occasionally stir-fried, deep-fried, and roasted (Durst et al., 2010).

Numerous meals, including pastries and items that resemble meat, have been fortified with *T. molitor* larvae (Melgar-Lalanne et al., 2019). The insect has also been added (2%, w/w) to corn tortillas. In a study, Aguilar-Miranda et al. (2001) reported that maize tortillas with 7.14% *T. molitor* larval flour recorded a 2% greater protein content. The emulsification capabilities of freeze-dried *T. molitor* larvae-enriched emulsified sausages were also enhanced (Kim et al., 2016). Meat batter incorporated with edible silkworm pupae (*Bombyx mori*) and transglutaminase exhibited enhanced protein and ash content and reduced cooking loss, improving its physicochemical attributes (Park et al., 2017).

Kinyuru et al. (2015) reported that Winfood Classic, a complementary food containing oven-dried termites and dagaa fish had higher levels of protein, energy, fat, and zinc than the control samples, which had no termites and dagaa fish. The findings confirmed that the product can be consumed as a complementary food. In a separate study, Koffi et al. (2013) indicated that biscuits manufactured from up to 25% deffated *Macrotermes subhyalinus* flour mixed with sorghum flour recorded improved protein and mineral contents. Cinereous cockroach (*Nauphoeta cinerea*) flour was also adequately sanitary with a good nutritional profile (De Oliveira et al., 2017). Furthermore, the technical and sensory qualities of wheat bread were unaltered by the inclusion of insect flours (De Oliveira et al., 2017).

Approximately 70% to 95% of animal species are insects, making them the most diverse category (Chapman, 2009). Consequently, insects are the most suitable feedstock for human consumption. India, Thailand, China, and Mexico are the top four nations that consume insects (Jongema, 2017). Nevertheless, the extent, species, and methods of consuming insects as food or feed differ due to geographical and cultural variances.

Insects are particularly valued for their nutritional content. For instance, *T. molitor* and *H. illucens* larvae, are commonly applied as feed as they offer significant lipid and protein levels. *Tenebrio molitor* larvae contain approximately 24.3%-27.6% protein and 12%-12.5% lipids comparable to meat (Ghaly & Alkoaik, 2009). Meanwhile, the nutritional quality of *H. illucens* larvae varies with the substrate employed during rearing. For example, larvae supplied with palm kernel meal recorded crude protein and lipid levels of 42.1%-45.8% and 27.5%, respectively (Rachmawati et al., 2010). Consequently, adjusting the substrate allows the customisation of crude protein and lipid content to meet specific customer requirements.

Acheta domesticus are freeze-dried to produce protein bars, flour and pasta. The freeze-drying method preserves the nutritional content of the insect despite being expensive (Ratti, 2001). *Acheta domesticus* contains one of the highest protein values among edible insects at 64.4%–70.8% dry weight, considerably higher than conventional protein sources (Mariod et al., 2017). In India, *Oecophylla smaragdina* and *Samia ricini* larvae are sun-dried in particular regions, which could reach up to 40°C. The nation also receives ample sunlight throughout the year (Oldenborgh et al., 2017). Sun drying is also cost-effective and does not require any equipment.

Insects sold as snacks, lollipops, and candies are common in regions with years of practice in entomophagy, including Thailand, Central African countries, Cambodia, and China. In China, edible insect consumption is significantly common, as over 324 species from 11 groups of insects have been classified as edible (Feng et al., 2017). Gahukar (2018) reported that more than 82 insect species from nine orders are consumed regularly in Indian cuisines.

Using insects as animal feed and human food requires distinct quality and safety regulations. Key considerations for animal feed include microbial hazards, chemical hazards, and allergens, with regions such as the European Union, North America, East Asia, Australia, and Nigeria implementing regulations on insect feed to support its potential as a novel feed resource in the future (Lee et al., 2022). Conversely, human food must adhere to more stringent laws prioritising nutritional value, sensory qualities, and cultural acceptance. For human use, factors including microbiological safety, allergenicity, and heavy metal residues become even more crucial (Henderson, 2022; Lee et al., 2022). This differentiation needs specialised processing, pre-treatment, and storage techniques for insect products intended for certain applications.

Health Risks and Safety Considerations of Insect Protein

Insect protein is increasingly recognised as a sustainable and nutritional alternative to traditional protein sources. However, its intake poses a number of health hazards and safety concerns that must be addressed to assure consumer safety. The potential food safety problems related to edible insects may be categorised into three categories: chemical, biological, and allergic (Murefu et al., 2019).

Among these, chemical hazards are a major concern, particularly due to pesticide residues, mycotoxins, and heavy metals (Murefu et al., 2019). Wild-harvested edible insects may contain pesticide residues due to their uncontrolled feeding on pesticide-sprayed vegetation, leading to the accumulation of residues in their body and eventually increasing the risk of food poisoning for consumers. For example, Murefu et al (2019) found that insect samples contained high levels of chlorinated and organophosphorus pesticides, with concentrations reaching 49.2 μg/kg and 740.6 μg/kg, respectively. Pesticide residues have been reported in edible insects such as *T. molitor* larvae, *Musca domestica* larvae and *H. illucens* larvae (Charlton et al., 2015; Gao et al., 2014; Van der Fels-Klerx et al., 2016). However, with the current development of edible insect farming, which controls their nutrition, it is feasible to create pesticide-free edible insects (Murefu et al., 2019).

Mycotoxins are a category of harmful secondary metabolites generated in the food chain by fungi that infect crops before and after harvest (Evans et al., 2022). The mycotoxins that have been studied include aflatoxins, fumonisins, zearalenone (ZEN), vomitoxin or deoxynivalenol (DON), and ochratoxins (OTAs) (Evans et al., 2022). Mycotoxins may be found in the feed substrate on which edible insects are cultivated (Muresu et al., 2019). Presence of mycotoxins with varying concentration has been reported in *Imbrasia belina* caterpillar, *Bunaea alcinoe* caterpillar, stink bugs and *T. molitor* larvae (Braide et al., 2011; Musundire et al., 2016; Simpanya et al., 2009; Wynants et al., 2017).

Heavy metals also pose significant concerns as chemical hazards in edible insects. Heavy metals such as lead, mercury, arsenic, and cadmium can cause systemic toxicities at low exposure levels, leading to adverse health effects in humans and animals (D'Souza & Peretiatko, 2002; Jan et al., 2015). Heavy metal accumulation in edible insects is influenced by various factors such as insect species, growth phase, and feed substrate (Van Huis, 2021). Cadmium, lead, mercury, and arsenic are essential heavy metals that accumulate in edible insects based on the metal element, insect species, and development stage (Diener et al., 2015; Van der Fels-Klerx et al., 2018). Cadmium and arsenic have been found to accumulate in black soldier fly larvae and yellow mealworm larvae (Van der Fels-Klerx et al., 2018). In Thailand, mercury, lead, cadmium and arsenic were detected at low concentrations in four edible insects, which are the mulberry silkworm, scarab beetle, house cricket and Bombay locust (Köhler et al., 2019).

Beyond chemical risks, biological contaminants also pose serious issues when it comes to the consumption of edible insects. Both spoilage and pathogenic microorganisms can be inherent in the level of contamination depending on the insect type, processing methods, handling procedures, and hygiene practices (Rumpold & Schlüter, 2013). Pathogenic bacterial genera such as *Escherichia*, *Staphylococcus*, and *Bacillus* can infect both humans and invertebrates, including insects, posing health hazards to consumers of edible insects, even in the absence of contamination from other sources (Grabowski & Klein, 2017). Pathogenic microorganisms have been identified from a variety of edible insect species and are frequently linked to foodborne illness outbreaks (Murefu et al., 2019).

Edible insects processed and sold in Thailand harbour many potentially human pathogenic bacterial genera, including *Vibrio*, *Streptococcus*, *Staphylococcus*, *Clostridium* and *Bacillus* (Osimani et al., 2017). Moreover, consumption of edible insects may also lead to the transmission of parasitic foodborne diseases, with wild-gathered insects having a higher risk of transmission than farmed insects due to their unconfined eating habits (Murefu et al., 2019). Boye et al. (2012) reported that consumption of ants transmits *Dicrocoelium dendriticum*, a zoonotic parasite to humans.

In addition to chemical and biological risks, allergenicity also poses a significant concern in insect consumption. Due to their high protein content, edible insects, particularly those containing arginine kinase, may pose allergy risks (Murefu et al., 2019). Since insects and crustaceans are linked, it is possible that they might result in food allergies (Francis et al., 2019). In addition to arginine kinase, α-amylase and tropomyosin are other often found allergens associated with edible insects (Srinroch et al., 2015). A broad population may be at risk for allergic responses, as evidenced by research done in Belgium that indicated 19% of persons were sensitised to grilled samples of *A. domesticus* and *T. molitor* insects (Francis et al., 2019).

Although there are limited studies on adverse effects, eating insects has been connected to 7.6% of allergic responses in Laos and 18% of fatal food reactions in China (Barennes et al., 2015; Ji et al., 2009). Insects such as mealworm, silkworm, sago worms, caterpillars, grasshopper, locust, bee, cicada, *Bruchus lentis* and *Clanis bilineata* have been reported to cause food allergy (de Gier & Verhoeckx, 2018). Allergic responses to edible insects have been reported in various regions, including silkworm pupa in China, mopane caterpillars (*Imbrasia belina*) in Africa, and locusts and grasshoppers in India (Chakravorty et al., 2011; Ji et al., 2008; Kung et al., 2011). Additionally, carmine, a food pigment made from female cochineal insects (*Dactylopius coccus*), is the only insect-derived food additive linked to allergy reactions to date (de Gier & Verhoeckx, 2018). In order to protect consumers, such responses emphasise the necessity of additional allergenicity research and explicit labelling of items derived from insects.

Future Prospects

The widespread practice of consuming insects as feedstocks and snacks in the Asia-Pacific region reflects the cultural practices of the population in the region. Moreover, the action aligns with several Sustainable Development Goals (SDGs). In the Asia-Pacific region, particularly in rural areas, entomophagy is an accepted diet. The practice meets the SDG 2 objective, Zero Hunger, as insects provide a nutrient-rich source of proteins and essential nutrients to combat hunger and malnutrition (FAO, 2013; Yen, 2015).

Insect commercialisation creates job opportunities, fulfilling the eighth SDG, decent work and economic growth (United Nations Development Programme, n.d). The industry promotes livelihoods, economic growth, and poverty reduction through employment opportunities, particularly in rural regions, and fosters entrepreneurship and innovation in food production. The evolving methods and cultural practices in insect consumption highlight the necessity to explore sustainable food systems, hence meeting the SDG 12 aim of responsible consumption and production.

Various factors influence consumer acceptance of dried insects as food products. Studies indicated that customer approval from different areas and demographic groups varies significantly (Van Huis et al., 2013). Several Western nations indicated a major cultural barrier to consuming insects, frequently owing to the "yuck" factor or unfamiliarity with insects as food (Verbeke, 2015). Nonetheless, in regions where entomophagy is common, such as Africa, Asia, and Latin America, dried insects are widely tolerated and even regarded as a delicacy (Van Huis et al., 2013). Positive sensory experiences, such as good taste and texture, might improve acceptance (Caparros Megido et al., 2014). Knowledge of insect nutritional advantages, including their considerable protein content, vital amino acids, vitamins, and minerals, might also have positive effects on customer perceptions (Van Huis et al., 2013).

The Islamic perspective on entomophagy is crucial in understanding its compatibility with Islamic dietary laws (Halal). Proper pre-treatments, drying processes, and handling methods are essential in ensuring food safety. Furthermore, environmental and sustainability considerations within Islamic principles require consideration. Further research is also necessary to clarify the Islamic stance on entomophagy and promote its adoption within the Muslim community.

Understanding the Kosher perspective on entomophagy is equally crucial for those observing Jewish dietary laws (kashrut). The Jewish dietary laws known as kashrut impose certain limitations on the types of animals, including insects, that can be eaten. According to certain traits in Jewish scripture, eight kinds of insects are kosher (Jagadeesan et al., 2024). It has been shown that locust eating was quite common throughout the time of the Mishnah and Talmud. However, the custom was only maintained among Yemeni Jews and in some regions of northern Africa due to the lack of clarity on insects' wings and swarming animals, which caused a significant reduction (Hewamanage, 2016). All crawling animals on the ground, including insects with wings and swarming critters, are not kosher (Mclaughlin, 2017).

CONCLUSION

Applicable pre-treatment and drying methods depend upon insect type and desired final product. Generally, blanching is preferred due to its immediate effects compared to other pre-treatment processes. Although microwave and freeze-drying are the preferred methods, freeze-drying stands out as the optimal technique for preserving insect quality and appearance across species. Nevertheless, despite extensive exploration of different pre-treatments and drying approaches, no universally established guidelines are available.

Differences in edible insect species and their developmental phases necessitate species- and stage-specific pre-treatment and processing techniques to guarantee optimal quality and safety. Considerations must include nutritional composition, structural qualities, and possible pollutants. For instance, high-fat larvae may need lipid stabilisation, but adults with rigid exoskeletons may require deshelling or grinding. Safety precautions like blanching or gut-emptying can address microbial loads and pollutants. For applications involving human food and animal feed, efficient processing is ensured by adapting techniques to these variances.

Future studies might consider investigating novel pre-treatment and drying processes for insects that have yet to be extensively researched. Insect protein offers a promising solution to global protein shortages, providing nutritional, environmental, and ethical benefits. To ensure safety, addressing chemical residues, biological contaminants, and potential allergens through controlled farming, processing, and clear labelling is essential. With these safeguards in place, insect protein, along with other new options, can meet the rising protein demand while reducing the environmental impact of food production.

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