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Review

Food Wastes as a Potential new Source for Edible Insect Mass Production for Food and Feed: A review

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Abstract: About one-third of the food produced annually worldwide ends up as waste. A minor part of this waste is used for biofuel and compost production, but most is landfilled, causing environmental damage. Mass production of edible insects for human food and livestock feed seems a sustainable solution to meet demand for animal-based protein, which is expected to increase due to rapid global population growth. The aim of this review was to compile up-to-date information on mass rearing of edible insects for food and feed based on food wastes. The use and the potential role of the fermentation process in edible insect mass production and the potential impact of this rearing process in achieving an environmentally friendly and sustainable food industry was also assessed. Food waste comprises a huge nutrient stock that could be valorized to feed nutritionally flexible edible insects. Artificial diets based on food by-products for black soldier fly, house fly, mealworm, and house cricket mass production have already been tested with promising results. The use of fermentation and fermentation by-products can contribute to this process and future research is proposed towards this direction. Part of the sustainability of the food sector could be based on the valorization of food waste for edible insect mass production. Further research on functional properties of reared edible insects, standardization of edible insects rearing techniques, safety control aspects, and life cycle assessments is needed for an insect-based food industry.

Keywords: edible insects; food wastes; insect mass production; fermentation; sustainability

1. Introduction

Entomophagy, i.e., the practice of eating insects as food, formed part of the prehistoric diet in many areas worldwide [1,2]. Over the millennia since then, it has been a regular part of the diet of many people from various cultures throughout the world [3,4]. Globally, more than two billion people, mainly in Asia, Africa, and South America, are estimated to practice entomophagy [2,4,5], with more than 2000 edible insect species being used for this purpose [6]. In Western culture, however, entomophagy is not accepted and is considered a disgusting and primitive behavior, while insects are associated with pests [7]. However, this taboo seems to be weakening in recent years, as eating habits have been changing and a new trend for insect-based products and incorporation of entomophagy into the Western diet has begun [8,9].

In the near future, demand for animal-based food protein is expected to increase by up to 70% [10] due to exponential growth in the global population, which is predicted to reach 9 billion by 2050 [3,8]. The increased food production required to meet this demand will be accompanied by further exhaustion of water, agricultural, forestry, fishery, and biodiversity resources, with negative environmental impacts [11]. When the problem of climate change is added to these concerns, then global food security becomes an even more crucial issue [12,13].

Edible insects are called the insect species which can be used for human consumption but also for livestock feed as a whole, parts of them, and/or protein, and lipid extract [11,14,15]. Edible insects seem a promising alternative solution to achieving food security in the upcoming global food crisis [16], because they provide some significant advantages for human nutrition, including high protein, amino acids, lipids, energy, and various micronutrients [17,18]. Moreover, compared with livestock, insect rearing has a lower environmental impact as multiple and various food sources can be used, greenhouse gas emissions are low, the water and space requirements are low, and the feed conversion rate is high [7,11] . In addition to serving as food and feed, insects can also contribute significantly to food sustainability through biowaste degradation and conversion into food, feed, and fertilizers [19]. Furthermore, they can help preserve biodiversity [20] and assist in plant pollination and pest control [9].

In the global food industry, around 1.3 billion tonnes of various food wastes are discarded every year [21]. The waste generated in the food industry originate mainly from primary production, food processing, wholesale and logistics, combined with retail and markets, food service, and households. For 2012, the estimated volume of food waste for the EU alone was about 88 million tonnes [22]. In the USA, almost 45 million tonnes of fresh vegetables, fruits, milk, and grain products are wasted annually [23]. According to Baiano (2014), up to 42% of total food waste is produced in households [24].

In many cases, food waste residues are difficult to utilize for the recovery of value-added products due to their biological instability, potentially pathogenic nature, high water content, rapid autoxidation, and high level of enzymatic activity [25]. On the other hand, this biomaterial comprises a huge nutrient stock [26] and could be valorized through biodegradation by various edible insect species in a mass production system [9,27,28].

The aim of this review was to compile up-to-date information on rearing edible insects for food and feed purposes using food waste as a substrate. The impact of this bioconversion system in achieving an environmentally friendly and sustainable food industry was also considered.

2. Edible Insect Species Commonly Mass Produced for Food, Feed, and other Applications

In general, within edible insect rearing and gathering three main strategies are followed: wild harvesting (not farming), semi-domestication (outdoor farming), and farming (indoor farming) [11]. Globally, 92% of edible insect species are wild-harvested, but semi-domestication and farming can provide a food supply in a more sustainable way [3]. Farming of insects for food and feed has recently begun [7].

Regarding consumer acceptance, distribution, rearing conditions, environmental impact, food safety aspects, nutritional value, and use as a component in the diet of farmed animals, pets, and fish, the main commercial edible species harvested in the wild worldwide, but also used for industrial large-scale production, belong to six major orders: Coleoptera, Hymenoptera, Isoptera, Lepidoptera, Orthoptera, and Diptera [15,29].

The most commonly used commercial insects in mass production are mulberry silkworm, waxworm, yellow mealworm, house cricket, black soldier fly, housefly (indoor farming), palm weevil, bamboo caterpillar, weaver ant, grasshopper (outdoor farming), eri silkworm, muga silkworm, giant hornet, and termite (wild farming) [15,30]. The insects most commonly used as animal feed are black soldier fly, housefly, mealworm, beetles, locusts, grasshoppers, crickets, and silkworm [31]. Some edible insect species are also used for medical applications, e.g., *Lucilia sericata* (common green bottlefly) is used as a biological indicator of post-mortem interval (PMI), in human pathology, while its larvae are used in human medicine for healing chronic injuries that cannot be cured with conventional treatments [32]. Moreover, the allantoin secreted by the larvae is used in the treatment of osteomyelitis [30]. Other applications of edible insects include biodegradation of polystyrene in the environment using *Tenebrio molitor* mealworm [33,34], use of black soldier for municipal organic waste management [35], and the use of non-mammalian models like *Galleria mellonella* larvae, also known as waxworm, to model human diseases caused by a number of bacterial pathogens [36].

The most common commercially reared edible insects and their applications for human food and animal and fish feed, as medicines, for component extraction and as environmental treatments are listed in Table 1.

Table 1. Summary of the edible insect species most commonly reared for food and feed, the developmental stage at which they are used, the type of farming system, and commercial applications.

Insect species	Common name	Developmental Stage	Source	Application	Reference
Bombyx mori	Mulberry silkworm	Larvae, pupae	Farming	Human food, animal feed	[11,15,37]
Tenebrio molitor	Yellow mealworm	Larvae	Farming	Human food, feed for pets, zoo animals and fish, polystyrene degradation	[15,28,31,33,34]
Galleria mellonela	Waxworm	Larvae	Farming	Human food, model for human diseases study	[7,30,36]
Rhynchophorus ferrugineus	Red palm weevil	Larvae, pupae	Semi-cultivation	Human food	[38,39]
Rhynchophorus phoenicis	Palm weevil	Larvae	Semi-cultivation	Human food	[39,40]
Acheta domesticus	House cricket	Adult	Farming	Human food, pet food, protein extraction	[15,41]
Gryllus bimacalatus	Mediterranean field cricket	Adult	Farming	Animal feed	[30]
Imbrasia belina	Mopane worm (MW)	Larvae (caterpillar)	Farming	Human food	[42]
Musca domestica	Housefly	Larvae	Farming	Animal and fish feed	[43,44]
Lucilia sericata	Green bottlefly	Larvae (maggot)	Semi-cultivation	Animal and fish feed, Medical treatment	[30–32]
Omphisa fuscidentalis	Bamboo caterpillar	Larvae	Semi-cultivation	Human food	[1,4]
Oecophylla smaragdina	Weaver ant	Adult, larvae, pupae, eggs	Semi-cultivation	Human food, medicine use	[38,45]
Patanga succincta	Grasshopper	Adult	Wild harvesting	Human food	[46]
Oxya spp.	Grasshopper	Adult	Wild harvesting	Human food	[29]
Locusta migratoria	Locust	Adult, nymphs	Farming, wild harvesting	Human food, pet food and fish bait	[11,47,48]
Apis mellifera	Honeybee	Adult	Farming, semi-cultivation	Human food, medical uses (honeybee venom, propolis, royal jelly)	[7,30,49]
Hermetia illucens	Black soldier fly (BSF)	Larvae	Farming	Human food, animal feed	[50]
Macrotermes spp.	Termite	Adult	Wild harvesting	Human food	[51,52]
Encosternum spp.	Stinkbug	Adult	Wild harvesting	Human food	[29,53]

Vespula spp.	(Social) wasp	Larvae	Wild harvesting	Human food	[54,55]
Panchoda marginata	Sun beetle	Larvae	Farming	Human food, animal and fish feed	[7,56]

3. Edible Insect Species that can Utilize Food Waste as Feed and their Nutritional Requirements in Mass Production

To date, around 1 million insect species have been described and classified, but the actual number of insect species on Earth is estimated to be between 4 and 30 million. Jongema (2015) compiled a detailed catalogue listing 2037 edible insect species [6], but the actual number of insect species suitable for human food or animal feed applications is still unknown [3].

In recent years, low cost and effective diets, so called artificial diets, are used in lab and/or industry scale in order to rear insects for various purposes (e.g., edible insects, insects as pest predators for pest biological control etc.) [57–59]. Various artificial diets have been introduced for insect rearing, but even the most promising of these is still inferior to natural nutrient sources [60]. The insect species most widely farmed for food and feed purposes are mainly omnivores, which are able to utilize various food sources and thus show broad nutritional flexibility. For this reason, their nutritional requirements and feed rate when fed an artificial diet are difficult to determine [30,61,62]. Due to their nutritional flexibility, the use of low-value food sources can be ideal for large-scale farming of edible insects [11].

A balanced diet composed of organic by-products can be as suitable for the successful growth of mealworm species as the diets used by commercial breeders [28]. It has been reported that an organic food-based diet is critical for larval growth, mass density, and colony maintenance [63]. Recycling of low-quality, plant-derived waste and its conversion into a high-quality feed rich in energy, protein, and fat can be achieved with mealworms in a relatively short time [31]. Moreover, the omnivorous house cricket *Acheta domesticus* can be fed on a large range of organic materials, making it easy to farm in a system producing six or seven generations per year [31].

Most studies with encouraging results regarding artificial diets based on food wastes or mixtures of wastes have been carried out using edible mealworm (*Tenebrio molitor* L., Coleoptera: Tenebrionidae), black soldier fly (*Hermetia illucens*, Diptera: Stratiomyidae), housefly (*Musca domestica*, Diptera: Muscidae), and Cambodian cricket (*Teleogryllus testaceus*, Orthoptera: Gryllidae) and have used raw food material as the insect feed [28,31,60,62,64–67].

Farmed edible insects that utilize food materials and wastes during rearing are summarized in Table 2.

Table 2. Summary of various edible insect species reared on food wastes and their characteristics.

Order	Family	Species	Common name	Developmental Stage	Degraded Material	Reference
Coleoptera	Tenebrionidae	*Tenebrio molitor* L.	Mealworm	Larvae	Spent grains and beer yeast, bread remains, biscuit remains, potato steam peelings, maize distillers' dried grains with solubles	[28]
Coleoptera	Tenebrionidae	*Tenebrio molitor* L.	Mealworm	Larvae	Mushroom spent corn stover, highly denatured soybean meal, spirit distillers' grains	[64]
Coleoptera	Tenebrionidae	*Zophobas atratus* Fab.	Mealworm	Larvae	Spent grains and beer yeast, bread remains, biscuit remains, potato	[28]

					steam peelings, maize distillers' dried grains with solubles	
Coleoptera	Tenebrionidae	*Alphitobius diaperinus*	Mealworm:	Larvae	Spent grains and beer yeast, bread remains, biscuit remains, potato steam peelings, maize distillers' dried grains with solubles	[28]
Diptera	Stratiomyidae	*Hermetia illucens*	Black soldier fly	Larvae	Waste plant tissues, garden waste, compost tea, catering waste, food scraps	[68]
Diptera	Muscidae	*Musca domestica*	Housefly	Larvae	Mixture of egg content, hatchery waste, and wheat bran	[31]
Orthoptera	Gryllidae	*Acheta domesticus*	House cricket	Adult	Grocery store food waste after aerobic enzymatic digestion, municipal food waste heterogeneous substrate	[41]
Orthoptera	Gryllidae	*Teleogryllus testaceus*	Cambodian field cricket	Adult	Rice bran, cassava plant tops, water spinach, spent grain, residues from mungbean sprout production	[67]

In general, the major macronutrients required for insect mass production are (a) carbohydrates, which serve as an energy pool but are also required for configuration of chitin (exoskeleton of arthropods) [60], (b) lipids (mainly polyunsaturated fatty acids such as linoleic and linolenic), which are the main structural components of the cell membrane, and also store and supply metabolic energy during periods of sustained demands and help conserve water in the arthropod cuticle [29,59,69], and (c) the amino acids leucine, isoleucine, valine, threonine, lysine, arginine, methionine, histidine, phenylalanine, and tryptophan, which insects cannot synthesize [70], and tyrosine, proline, serine, cysteine, glycine, aspartic acid, and glutamic acid, which insects can synthesize, but in insufficient quantities at high energy consumption [61,70]. The essential micronutrients in insect rearing are (a) sterols, which insects cannot synthesize, (b) vitamins, and (c) minerals [30].

The nutrient requirements of edible insects in mass production are summarized in Table 3.

Table 3. Summary of the nutrient requirements of edible insects (adapted from [30,60]).

Macronutrients			**Micronutrients**		**Minerals**
Carbohydrates	**Lipids**	**Proteins**	**Sterols *****	**Vitamins**	**Elements *******
Glucose * Fructose * Galactose * Arabinose ** Ribose ** Xylose ** Galactose ** Maltose * Sucrose *	Linoleic (Pfa)*** Linolenic (Pfa) *** Phospholipids ****	Globulins Nucleoproteins Lipoproteins Insoluble proteins Amino acids: Leucine *** Isoleucine *** Valine ***	Cholesterol Phytosterols (β-sitosterol, campesterol, stigmasterol) Ergosterol	A: Retinol + α-and β-carotene (Ls) B1: Thiamin (Ws) B2: Riboflavin (Ws) B3: Nicotinamide (Ws) B4: Choline (Ws) B5: Pantothenic acid (Ws)	Hydrogen Oxygen Carbon Nitrogen Calcium + Phosphorus +++ Chlorine

	Threonine *** Lysine *** Arginine *** Methionine *** Histidine *** Phenylalanine *** Tryptophan *** Tyrosine **** (major component of sclerotin) Proline **** (important during flight initiation) Serine **** Cysteine **** Glycine **** Aspartic acid **** Glutamic acid ****		B6: Pyridoxine (Ws) B12: Cobalamine (Ws) C: Ascorbic acid (Ls) D: Cholecalsiferol and Ergocalsiferol (Ls) E: α-tocopherol (Ls) K: Phyloquinone (Ls)	Potassium +++ Sulphur Sodium +++ Magnesium +++ Iron ++ Copper +++ Zinc +++ Silicone Iodine Cobalt Manganese +++ Molybdenum Fluorine Tin Chromium Selenium Vanadium

*: Insects able to absorb and metabolize; **: Insects able to absorb but not metabolize; Pfa: Polyunsaturated fatty acids; ***: Insects unable to synthesize; ****: Insects able to synthesize; Ws: Water-soluble; Ls: Lipid-soluble; *****: Listed in order of importance as essential for living matter (from top down). Minerals consist of combinations of cations and anions of elements; +++: Important for insect growth; ++: Important in enzyme pathways including DNA synthesis; +: Important to a lesser extent, important role in muscular excitation.

Food industry organic wastes are produced in vast quantities and can be valorized for various purposes, e.g., as biofuels, crop fertilizers, pharmaceuticals, functional foods, etc. [25]. The largest quantities are generated by the fruit, vegetable, olive oil, fermentation, dairy, meat, and seafood industries [23]. Food waste comprises a mixture of various food residues, e.g., bread, pastry, noodles, rice, potatoes, meat, and vegetables [21].

Insects are much more efficient at converting feed to body weight than conventional livestock and can be reared on organic waste streams, transforming these into high-value food and feed [31]. The use of food wastes in rearing edible insects is a quite new and promising approach [7,11]. For this purpose, various artificial food waste-based diets covering the nutritional needs of farmed insects have been proposed, without pre-treatment of the biomaterial [28,31,67] (see also Table 2).

The chemical composition and nutritional value of various wastes that have already used in insect rearing are summarized in Table 4.

Table 4. Summary of chemical composition of various food materials and wastes which can be used for rearing edible insects (mainly adapted from DTU-Food database [71]).

Food *	Chemical Composition	Reference
Wheat bran	Total N (2.560%), protein (16.2%), available carbohydrates (24.6%), dietary fiber (40.2%), total fat (5.3%), ash (5.4%), water (8.4%), vitamins (C, E, K1, B1, B2, B3, B5, B6, B9), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se, Mo, Co, Ni, Cd, Pb), carbohydrates (fructose, glucose, sucrose), saturated fatty acids (C16:0, C18:0, C20:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9, C20:1 n-11), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3, C20:4 n-6), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,72]

Soy flour	Total N (6.520%), protein (37.2%), available carbohydrates (20.2%), dietary fiber (10.4%), total fat (22.2%), ash (5.1%), water (5.1%), vitamins (A, β-carotene, E, K1, B1, B2, B3, B5, B6, B9), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Z, In, Mn, Cr, Se, Ni, Hg, Cd, Pb), carbohydrates (sucrose, starch, exoses, pentoses, uronic acids, cellulose, lignin), saturated fatty acids (C12:0, C14:0, C16:0, C18:0, C20:0, C22:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9, C20:1 n-11), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,73]
Spent grain	Total N (1.890%), protein (11.0%), available carbohydrates (64.3%), dietary fiber (8.5%), total fat (4.2%), water (8.7%), vitamins (B1, B2, B3, B6, B9, E), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se, Mo, Co, Ni, Hg, Cd, Pb), amino acids (isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	([71,74]
Spent brewer's yeast	Total N (1.340%),%), protein (8.4%), available carbohydrates (12.7%), dietary fiber (6.2%), total fat (1.9%), ash (1.8%), water (69.0%), vitamins (B1, E, B2, B3, B5, B6, B7, B9, C), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Z, In, Mn, Se, Ni, Cd), carbohydrates (mannose, β-(1,3), (1,6)-glucan, α-(1,4)-glucan, chitin) saturated fatty acids (C12:0, C16:0, C18:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9), polyunsaturated fatty acids (C18:2 n-6), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine), nucleic acids	[71,75–77]
Bread remains	Total N (1.400%), protein (8.0%), available carbohydrates (48.0%), dietary fiber (4.0%), total fat (4.3%), ash (1.8%), water (33.9%), vitamins (E, B1, B2, B3, B5, B6, B7, B9), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Z, In, Mn, Cr, Se, Ni, Hg, As, Cd, Pb), carbohydrates (fructose, glucose, sucrose), saturated fatty acids (C14:0, C16:0, C18:0, C20:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9, C20:1 n-11), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,78]
Potato steam peelings	Starch (25%), non-starch polysaccharide (30%), acid insoluble and acid soluble lignin (20%), protein (18%), lipids (1%), and ash (6%),	[71,79]
Potato	Total N (0.324), protein (2.0%), available carbohydrates (15.9%), total fat (0.3%), dietary fiber (1.4%), ash (0.9%), water (79.5%), vitamins (A, B1, B2, B3, B5, B6, B7, B9, C), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se, Ni, Hg, As, Cd, Pb), carbohydrates (fructose, glucose, sucrose, starch, exoses, pentoses, uronic acids, cellulose), saturated fatty acids (C16:0, C18:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[80]
Dry egg whites	Total N (13.200%), protein (82.3%), available carbohydrates (6.8%), dietary fiber (0.0%), total fat (0.0%), ash (5.1%), water (5.8%), vitamins (B1, B2, B3, B5, B6, B7, B9, B12, D, E), minerals and inorganics (Cl, Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine), cholesterol (16 mg/100 g)	[71,81]

Rice bran	Total N (2.24%), protein (13.4%), available carbohydrates (28.7%), dietary fiber (21.0%), total fat (0.0%), ash (10.0%), water (6.1%), vitamins (B1, B2, B3), minerals and inorganics (Na, K, Ca, P, Fe), carbohydrates (crude fiber 11.5%), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,82]
Carrot	Total N (0.11%), protein (0.7%), available carbohydrates (5.8%), dietary fiber (2.9%), total fat (0.4%), ash (0.7%), water (89.5%), vitamins (A, β-carotene, E, K1, B1, B2, B3, B5, B6, B7, B9, C), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se, Ni, Hg, As, Cd, Pb), carbohydrates (fructose, glucose, sucrose, hexoses, pentoses, uronic acids, cellulose, lignin), saturated fatty acids (C16:0, C18:0), monounsaturated fatty acids (C18:1 n-9), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3, C20:4 n-6), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,83]
Lettuce	Total N (0.204%), protein (1.3%), available carbohydrates (0.8%), dietary fiber (1.3%), total fat (0.4%), ash (0.8%), water (95.5%), vitamins (A, β-carotene, E, K1, B1, B2, B3, B5, B6, B7, B9, C), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn), carbohydrates (fructose, glucose, sucrose, starch, hexoses, pentoses, uronic acids, cellulose, lignin), saturated fatty acids (C12:0, C16:0, C18:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9, C20:1 n-11, C22:1 n-9), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3, C18:4 n-3, C20:4 n-6, C20:5 n-3, C22:5 n-3, C22:6 n-3), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,84]
Cassava plant	Total N (0.218%), protein (1.4%), available carbohydrates (36.3%), dietary fiber (1.8%), total fat (0.3%), ash (0.6%), water (59.7%), vitamins (A, β-carotene, B1, B2, B3, B5, B6, B7, B9, C), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn, In, Mn, Cr, Se, Ni, Hg, As, Cd, Pb), carbohydrates (fructose, glucose, sucrose, starch, hexoses, pentoses, uronic acids, cellulose, lignin), saturated fatty acids (C16:0, C18:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3, C20:4 n-6), amino acids (isoleucine, leucine, lysine, methionine, cysteine, phenylalanine, tyrosine, threonine, tryptophan, valine, arginine, histidine, alanine, aspartic acid, glutamic acid, glycine, proline, serine)	[71,85]
Peanut oil	Total N (0.000%), protein (0.0%), available carbohydrates (27.5%), dietary fiber (0.0%), total fat (72.5%), ash (0.0%), water (0.0%), vitamins (E, γ-tocopherol), minerals and inorganics (Na, K, Ca, Mg, P, Fe, Cu, Zn), saturated fatty acids (C16:0, C18:0, C20:0, C22:0, C24:0), monounsaturated fatty acids (C16:1 n-7, C18:1 n-9, C20:1 n-11), polyunsaturated fatty acids (C18:2 n-6, C18:3 n-3, C22:6 n-3, other fatty acids)	[71,86]

* Data refer to natural products that have not been processed or pre-treated.

4. Rearing Conditions and Insect Mass Technologies

Wild harvesting can potentially lead to depletion of natural insect species [3]. For a sustainable insect farming industry, cost-effective rearing, harvesting, and processing technologies are required [19]. The information required for industrial-scale mass production of insects from biowaste and agricultural organic residues for food and feed purposes is not complete, but much research is being conducted in this field and recent data seem very promising [30] (see also Table 2). The need for lower cost, more environmental friendly, and sustainable nutrient resources for insect mass technologies will increase as the production level increases [30]. In this regard, food biomass waste can comprise a potential source of ingredients for artificial diets used in edible insect industrial production [7,11,54].

The artificial diets used in insect mass production vary from liquid to solid, depending mainly on (a) the nutritional needs of the insect in question in terms of macronutrients, micronutrients and minerals (see also Table 3.); (b) the feeding adaptation of the insect, meaning the way that food is processed by the mouthparts before ingestion, as these are adapted to match the feeding needs. Insect species possessing sucking mouthparts are liquid feeders, those possessing biting mouthparts are solid feeders, and those that possess modified sucking mouthparts, so called piercing-sucking insects, are able to pierce the host and suck liquefied animal and/or plant tissues [30,60]; (c) the pre-manufacturing of the artificial diet. Liquid diets can be used after encapsulation using different materials (paraffin, PVC, polyethylene, polypropylene) to mimic artificial eggs, a treatment step needed for their containment and presentation [60], while liquids and slurries can be dried and concentrated so that can be dissolved in water or mixed with other ingredients. Semi-liquids are used in pellet or extruded form which can be ingested by insects with biting mouthparts and also by insects with sucking mouthparts [30]. Solids are presented as a feed mash with grinding and mixing of all raw materials, after pelleting of various raw materials or by extrusion. Solids can also be encapsulated with complex coacervation technology using proteins and polysaccharides [87].

The development of low-cost commercial diets is crucial for edible insect production at industrial scale [19]. In mass production, the mechanical equipment needed in an integrated production process, automation, mechanization, and monitoring technologies for rearing, harvesting, processing, packaging, and delivering edible insects must also be applied, in order to reduce costs and produce safe food products in large-scale quantities [5,19].

5. Nutritional Composition, Ingredient Characterization, and Food Functional Properties of Edible Insect Species

Insect farming conditions, insect developmental stage, the artificial diet selected, and the preparation and processing methods used (e.g., frying, boiling, drying) are factors that affect the nutritional composition of the reared insects [11]. Different diets composed of various food wastes have been reported to result in differences in the nutritional value of mealworm larvae [88]. However, most previous studies provide no details about the artificial diets and conditions used for insect rearing or about the preparation and process stages [29,53,54].

To date, data required in INFOODS/EuroFIR recommendations concerning the nutritional value of most common edible insect ingredients are lacking [29]. These data refer to protein, crude proteins, crude lipids, available carbohydrates, moisture, dry matter, energy, vitamins, and minerals.

The nutrient content of some of the most commonly reared edible insects reared on food wastes, in terms of crude proteins, crude lipids, available carbohydrates, vitamins, and minerals, is summarized in Table 5.

Table 5. Nutritional value of the most common edible insects reared on food materials and wastes.

Insect Species	Common Name	Develop-mental Stage	Crude Protein (% Dry Weight)	Lipids (% Dry Weight)	Carbohydrates, Vitamins, Minerals etc.	General Comments	Reference
Tenebrio molitor	Yellow mealworm	Larvae	70%–76%	6%–12%	c.a. 10%	Leucine, lysine, methionine + cysteine, threonine, and valine were the limiting amino acids comparing with FAO/WHO requirements. Major fatty acids were linoleic acid (C18:2, 30%–38%), oleic acid (C18:1, 24%–34%), and palmitic acid (C16:0, 14%–17%).	[66]
Tenebrio molitor	Yellow mealworm	Larvae	46.9%–48.6%	18.9%–27.6%	-	Mealworm species can be grown successfully on diets composed of organic by-products. Diet affects mealworm growth, development, and feed conversion efficiency. Diets high in yeast-derived protein appear favorable with respect to reduced larval development time, reduced	[28]

						mortality, and increased weight gain.	
**Zophobas atratus* Fab.	Mealworm	Larvae	34.2%–42.5%	32.8%–42.5%	-		[28]
**Alphitobius diaperinus*	Mealworm	Larvae	64.3%–65.0%	13.4%–21.8%	-		[28]
**Acheta domesticus*	House cricket	Adult	10.2%–28.6%	2.2%–12.0%	Carbohydrates (as crude fiber): 13.2%–28.9% Minerals: - Vitamins: -	It is possible, using very simple means, to rear local field crickets at ambient temperature in Cambodia. Agricultural and food industry by-products tested here also have potential for use as cricket feed, alone or in combination.	[67]
Acheta domesticus	House cricket	Adult	16%	-	-	Crickets fed the solid filtrate from food waste processed at an industrial scale via enzymatic digestion were able to reach a harvestable size and achieve feed and protein efficiencies. Crickets reared on waste substrates of sufficient quality might be the most promising path for producing crickets economically	[41]
Acheta domesticus	House cricket	Adult	15.6% ± 8.1%	4.56% ± 2.15%	Carbohydrates: - Minerals: Na, Fe, Zn, Ca, I Vitamins: B12, B2	Data show considerable variation within insect species	[29]

The research field concerning characterization of food functional properties of the most common edible insects (e.g., amino acid and lipid composition, foam ability and foam stability, water absorption capacity (WAC), fat absorption capacity (FAC), protein solubility, microstructure and color, rheological properties, etc.) is quite new. Some data is available, mainly for yellow mealworm, silkworm, house cricket, and housefly [54,89–91].

The food functional properties characterized for the most commonly reared edible insects are summarized in Table 6.

Table 6. Ingredient characterization and food functional properties of most common edible insect species.

Insect Species	Common Name	Developmental Stage	Characterization of Food Properties	Reference
Bombyx mori	Silkworm	Pupae	Amino acid analysis, lipid determination	[89]
Tenebrio molitor	Yellow mealworm	Larvae	Amino acid composition (ion exchange chromatography), protein quality (color, protein content, and molecular weight), molecular weight distribution of the insect protein fractions (SDS-PAGE), foam ability and foam stability, rheological properties	[90]
Tenebrio molitor	Yellow mealworm	Larvae	Amino acid composition, water absorption capacity (WAC), fat absorption capacity (FAC), protein solubility, microstructure and color, rheological properties	[91]
Acheta domesticus	House cricket	Adult	Amino acid composition (ion exchange chromatography), protein quality (color, protein content, and molecular weight), molecular weight distribution of the insect protein fractions (SDS-PAGE), foam ability and foam stability, rheological properties	[90]

Musca domestica	Housefly	Pupae	Moisture, protein, fat, ash, acid detergent fiber (ADF), neutral detergent fiber (NDF), minerals, amino acids, fatty acids, vitamins, and selected carotenoid determination	[92]
Apis mellifera	Honeybee	Eggs, larvae, adult	Determination of water content, crude fiber (structural carbohydrates), fat, free nitrogen extract and mineral salts, crude proteins, Vitamin B2	[93]
Hermetia illucens	Black soldier fly	Larvae	Moisture, protein, fat, ash, acid detergent fiber (ADF), neutral detergent fiber (NDF), minerals, amino acids, fatty acids, vitamins, and selected carotenoid determination	[92]

6. Fermentation Process in Edible Insect Chain Production

The fermentation process is applied during the edible insect production to the following stages:

(a) Valorization of food waste via fermentation and then use of edible insects, especially of the black soldier fly (BSF) [94,95]. The use of pre-fermentation can be performed for the waste stabilization and the food safety increasement. Moreover, the pre-fermentation can enhance the digestibility and bioavailability of nutrients to the insect larvae as most nutrients present in agricultural residue or byproducts are found in insoluble form [94]. The solid residues produced by processing of food waste via microaerobic fermentation (MF) and by black soldier fly larvae (BSF) have been proposed as soil fertilizers for plant growth [95].

(b) Use of fermentation by-products and food wastes as ingredients of artificial diets used for edible insect production. The edible mealworm species *Tenebrio molitor* L., *Zophobas atratus* Fab. and *Alphitobius diaperinus Panzer* were grown successfully on diets composed of organic by-products originating from beer brewing, bread/cookie baking, potato processing, and bioethanol production [28]. The *Hermetia illucens* edible insect, commonly named black soldier fly (BSF), was used for the biodegradation of kitchen residues, grass, sewage sludge, and separated solid material from biogas plants [68]. House crickets (*Acheta domesticus*) have been reared on diets based on food waste processed at an industrial scale via enzymatic digestion [41].

(c) Fermentation of the produced edible insect orders to increase the product's shelf-life and minimize the microbial risks for the consumers associated with edible insect consumption [96,97]. Successful acidification and effectiveness in product's safeguarding shelf-life and safety was achieved by the control of *Enterobacteria* and bacterial spores after lactic fermentation of flour/water mixtures with 10% or 20% powdered roasted mealworm larvae [97]. Techniques such as drying, acidifying, and lactic fermentation can preserve edible insects and insect products without the use of a refrigerator [16].

7. Legislation, Food Safety, and Potential Hazards Associated with the Edible Insect Food-to-Food Production Chain

The legislation concerning edible insects for food and feed varies worldwide. Current EU legislation is quite strict, with the application of two regulations: (a) Regulation 2015/2283 (European Food Safety Authority, EFSA) refers to the use of edible insects as food. Since these were not consumed in the EU before March 1997, they were initially considered 'novel foods' [98], while in the reformed regulations they are not specifically mentioned as novel foods [99]. However, if they are intended to be sold on the EU market, they require authorization from the EFSA. (b) Regulation EU 999/2001 refers to the use of edible insects as feed [100]. According to the International Platform on Insects for Food and Feed (IPIFF), only purified insect fat and hydrolyzed insect proteins are allowed to be used as feed for livestock, while non-hydrolyzed insect proteins can currently only be used and sold as pet food and for fur animals feeding while insects derived proteins are not allowed for use in pig or poultry feed [101]. The recent EU regulation No 2017/893 authorizes the use of insect proteins originating from seven insect species: Common Housefly (*Musca domestica*), Black Soldier Fly

(*Hermetia illucens*), Yellow Mealworm (*Tenebrio molitor*), Lesser Mealworm (*Alphitobius diaperinus*), House Cricket (*Acheta domesticus*), Banded Cricket (*Gryllodes sigillatus*), and Field Cricket (*Gryllus assimilis*), as feed in aquaculture [99].

Despite the strict regulatory framework, some EU countries are moving rapidly towards approval of edible insects for food and feed purposes [102]. The Netherlands tolerates the sale of edible insects included in the 'List of Edible Insects of the World' [6], while in Belgium the Agence Fédérale pour la Sécurité de la Chaîne Alimentaire (AFSCA) is carrying out a risk analysis on the sale of edible mealworms, crickets, and locusts as novel foods for the Belgian market [102,103]. In Germany, the EU regulation referring to processed animal proteins (PAPs) is interpreted such that insects PAPs are not allowed as feed (not even in aquaculture), as insects are not slaughtered, but this feed ban does not apply to live insects. Therefore a proposal has been made to Deutsche Landwirtschaftsgesellschaft (DLG) to list live insects as a direct animal feed ingredient [103]. In the United Kingdom the law is looser, allowing insects to be sold as food, but this will change relatively soon with a compulsory application procedure required for classification of insect-based food products [103]. In Switzerland, edible insects require authorization from the Federal Office of Food Safety and Veterinary Services (FFSVO) if they are intended to be sold on the open market [103], but recently FFSVO followed Belgium's policy in allowing particular insect species to be sold for food on the Swiss market [102].

In the US, the legislation on edible insects is also strict and more complex. The main authorities are the Food and Drug Administration (FDA), which regulates the industry and coordinates closely with the United States Department of Agriculture (USDA), and the Animal and Plant Health Inspection Service (APHIS) [102]. Concerning food insect-based products, these must conform to the standard practices of all other US foods, including *Salmonella* and *E. coli* testing and, as edible insects are considered food additives, they must follow FDA regulations as described in the Federal Food, Drug, and Cosmetics Act (FFDCA) for Food Additives [104]. All producers of edible insect products must also conform to all FDA manufacturing procedures, known as Good Manufacturing Practice (GMP) ([103].

In Canada, insect-based foods are considered 'novel' and the legislation is complex, as the food safety and public health standards are set by the Canadian Food Inspection Agency (CFIA), which falls under Health Canada, while novel food safety assessments are conducted under the Food Directorate [103]. In Australia and New Zealand, the food safety and hygiene standards are set by Food Standards Australia New Zealand (FSANZ), in which edible insects are classified as 'novel foods' (non-traditional foods), as in EU regulations, and require an assessment of public health and safety issues before their commercialization, unless they are prohibited from sale [102,103].

In Asia, Thailand appears to be a pioneer and one of the most progressive and innovative countries in edible insect mass production, collection, processing, transport, and marketing of cricket (with most farms being medium- or large-scale enterprises) and palm weevil larvae, but also weaver ants, bamboo caterpillars, and grasshoppers, which are collected from the wild or are harvested seasonally [38]. In China, despite its population and economic growth, mass production of edible insects has not yet been established [102].

In Africa, collaborations between African and European companies are being developed on value chain production in rearing, processing, distribution, and consumption of edible insects [103].

Industrial mass production of edible insects for food and feed is associated with the hazards involved in any food production chain, which can mainly be classified into heavy metals, mycotoxins, pesticide residues, and pathogens [16]. During the relevant processes in an insect-based food chain, the associated hazards concerning food safety are of two origins: (a) specific to the species and (b) related to rearing, processing practices, preservation, and/or transport conditions. They are classified into (a) chemical, (b) physical, (c) allergen, and (d) microbial [98,105].

The data concerning the potential hazards associated with a food-to-food production chain based on most common edible insects are summarized in Table 7.

Table 7. Hazards associated with food-to-food edible insect production.

General Hazard	Specific Hazard	Substance	Insect	Problem	Reference
Chemical	Pesticides/fungicides	Organophosphorus pesticides (malathion, sumithion)	Locust	Toxic, carcinogenic	[106]
	Persistent organic pollutants	Polybrominated diphenyl ether (PBDE)	House cricket	Bioaccumulative and toxic	[107]
	Heavy metals	Cd	Mealworm larvae (*Tenebrio molitor*)	Toxic, carcinogenic	[108–110]
		As	*Agrotis infusa* moth (Lepidoptera)	Toxic, carcinogenic	[111]
		Ld	Cricket	Toxic, carcinogenic	[105,112]
		Pb, Zn, Cu, Cd	Insect larvae (not specified)	Toxic, carcinogenic	
	Antibiotics	Chloramphenicol	Silkworm (*Bombyx mori*)	Prohibited use in animal production	[113]
	Insect toxic substances (for defense or repellent purposes, manufactured by the insect itself or accumulated by the insect via its environment or food)	Quinones	Bombardier beetle	-	[105]
		Cyanogenic toxic compounds (linamarin or lotaustralin)	Butterfly	-	[105]
		Melanization process because of the appearance of toxic products	Larvae of *Galleria mellonella* infected by a fungus	-	[105]
		Phenolic compounds: benzoquinone	Tenebrionidae: *Ulomoides dermesetoides*, flour beetles (adults) *Tribolium confusum* and *Tribolium castaneum*	Cytotoxic against the human lung carcinoma epithelial cell line A-549, DNA damage, possible carcinogen	[98]
		Venom (with bristles)	Coleoptera Larvae of *Trogoderma* spp.	Envenomation by dietary route, intestinal trauma due to the bristles found on the insect, ulcerative colitis	[105]
	Antinutritional substances	Hydrocyanic acid	Yam beetle (*Heteroligus meles*)	Anoxia, highly toxic	[114]
		Tannins	Yam beetle (*Heteroligus meles*), ant, termite, cricket, *Zonocerus variegatus* (grasshopper)	Protein precipitation, toxic	[114–116]
Physical	Foreign bodies	Materials from the processes as with any other processed food	-	Choking, injury, toxic, pain, allergy	[105]
	Insect parts	Sting, sharp rostrums, pines, coarse hairs, cuticles, wings	-	Choking, asphyxia, pain, allergy	[102]
Allergen	Insect colorants	Carmine dye	Cochineal insects (*Dactylopius coccus Costa, Coccus cacti* L.)	Anaphylaxis, urticarial, erythematous eruption	[98]
	Insect proteins	Lentil pest proteins	Lentil pests (*Bruchus lentis*)	Infestation	[117]
		Cross-reactive proteins: tropomyosin and arginine kinase	Mealworm (*Tenebrio molitor* L.)	Allergic shock	[118]

	Insect enzymes	-	Caterpillars (*Lophocampa caryae*)	Drooling, difficulty swallowing, pain, and shortness of breath	[98]
	Insect allergens	Venom	Bee, wasp, hornet	Anaphylactic shock, pain	[105]
		Chitin	Various edible insect species	Allergic reaction	[105]
Microbial	Parasitics	Human protozoan parasites	Black soldier fly larvae (*Hermetia illucens*)	Intestinal myiases	[119]
		Human protozoan parasites	Cockroaches and some Diptera	Gastrointestinal diseases, toxoplasmoses	[120]
	Bacteria	*Salmonella* *Shigella* *Vibrio* spp. *E. coli* *Yesrinia eneterocolitica* *Campylobacter* *Listeria monocytogenes* *Clostridium perfrigens*	Yellow meal beetle (*Tenebrio molitor*) Desert locust (*Schistocerca gregaria*) Silkmoth (*Bombyx mori*) Cricket (*Acheta domesticus*) Whole locust (*Locusta migratoria*)	Salmonellosis Shigellosis Vibriosis Diarrhea Yesriniosis Campylobacteriosis Listeriosis Clostridial myonecrosis	[121–123]
	Fungi	*Aspergillus, Penicillium, Fusarium, Cladosporium, Phycomycetes*	-	Mycotoxins	[98,105]
	Non-conventional transmissible agents (NCTA)	Prions	*Sarcophaga carnaria* pupae	Scrapie in hamsters	[105]
		Prion proteins	Fly larvae, mites	Scrapie (sheep), mad cow disease (cattle)	[124]

8. Edible Insect Rearing using Food Wastes: Towards Green and Sustainable Food Waste Management

The organic wastes generated in food industry processes are huge in volume and numerous in type [21,125]. Household food streams also comprise a significant quantity of waste that is not exploited but landfilled, causing environmental damage [126]. In recent years, food waste management has attracted much attention, as these waste products can be valorized with green technologies in a sustainable way [127,128] for the production of renewable chemicals, biomaterials, and biofuels [129].

In recent years, more and more consumers from the USA and various European countries, like Netherlands and Belgium, adopted the entomophagy trend as accepted [130,131].

The utilization of food wastes for edible insect rearing for food and feed seems a promising approach [16] and some of the most common edible insects have already been reared on food wastes with encouraging results (see Table 2). Regarding crickets reared on various food waste streams in a controlled temperature and relative humidity greenhouse, with pre-analyzed ratios of feed substrates (moisture content, total N, crude protein content, acid detergent fiber content, crude fat content, ash content) in order to assess their feed quality, the biomass accumulation was strongly influenced by the quality of the diet [41]. Regarding the rearing of three edible mealworm species (*Tenebrio molitor* L., *Zophobas atratus* Fab., and *Alphitobius diaperinus* Panzer) on food industry organic by-products, the effects of dietary composition on feed conversion efficiency and mealworm crude protein and fatty acid profile were assessed, indicating that larval protein content was not influenced by diet composition while larval fat composition was affected by the used diet to a certain extent [28]. The substitution of diets comprising of mixed grains with agro-food industry by-products can lower the cost of commercial mealworm rearing [64]. During an experimental design for rearing of black soldier flies on various food waste, the weight reduction of rested waste materials was determined, indicating the ability of the black soldier fly to degrade food and plant organic waste [68].

The effect of larval density on food utilization during mealworm *T. molitor* rearing on a determined mixture of food materials was evaluated, thus indicating that although the space considerations in insect mass rearing are important in reducing production costs, crowding larvae to save space may be counterproductive. Additionally, it was demonstrated that increasing larval density impacts negatively on the productivity resulting in a reducing efficiency of food conversion linearly, higher food expenses, and lower biomass production [63].

However, in the most up-to-date experimental trials, the artificial diets, the rearing conditions, the nutritional value of the reared edible insects on food wastes, the yield (in terms of protein, fat content, chitin, etc.), the quality, and also the cost-efficiency of each rearing technique are not determined. Additionally, in none of the referred technologies (see Table 2) is a technical and economical evaluation presented. In addition to this, the up-to-date trials have been applied with simple food mixtures of wastes which in many cases the proportion, chemical composition of the used food materials and wastes and the conditions of the feeding substrate (temperature, humidity, microbial stability, etc.) are not referred, thus resulting in a not standardized insect mass rearing method and technology. That, in the case of the valorization of household food wastes is very critical as they consist of a heterogeneous substrate of various food material [41] and the compilation of a standardized artificial diet based on this appears to be complicated. The compilation of an artificial diet based on simpler food industry mixtures of wastes (e.g., spent grain), seems easier and effective [28]. Finally, clinical trials of reared insects on food materials and wastes have not been performed in humans and animals until now.

9. Conclusions

Edible insects could provide a solution to meeting future increasing demand for animal-based protein. In addition, the sustainability of the food industry sector could be improved through the use of food wastes as new substrates or dietary components in large-scale processes rearing edible insects for human food and animal feed purposes. This bioconversion could also contribute significantly to reducing climate change and the environmental impacts of food and feed production. The first trials on feeding insects with food wastes have produced encouraging results. Prospective candidates for this purpose are the black soldier fly, which has also been tested for municipal organic waste management with very good results, mealworms, houseflies, and house crickets.

Although there are some promising experimental results on the valorization of food wastes for edible insect rearing, further research is needed on the creation of artificial diets based on food by-products for edible insect mass production, isolation, and characterization of the nutrient content of reared insects, techno-economical evaluation of used technology, food-to-food chain safety control evaluation, and life cycle assessments of farmed insect species, in order to enable establishment of a modern insect-based food industry. Additionally, the use of various fermentation by-products (e.g., yeast, bacteria, micro-algae, etc.) as potential materials for rearing edible insects, has been studied a little and not sufficiently, and further research on the combination of fermentation techniques with edible insect rearing technologies is proposed.

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