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Edible insects: An overview on nutritional characteristics, safety, farming, production technologies, regulatory framework, and socio-economic and ethical implications

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ABSTRACT

Background: Edible insects are considered as traditional foods in over 100 countries of Asia, Africa, and South America. Apart from this traditional aspect, edible insects are gaining increasing interest as alternative food sources for the increasing world population.

Scope and approach: The purpose of this research was to give an overview on several aspects of edible insects: nutritional characteristics; physical, chemical, and microbiological hazards; presence of antinutritional substances or allergens; gathering and farming; production technologies and patents; legal status worldwide; socio-economic and ethical implications.

Key findings and conclusions: Edible insects supply amounts of protein, fat, vitamins, and minerals comparable to those of meat. Although the studies on the environmental sustainability of insect farming are still few, it is generally recognized their limited requirements for land and reduced emissions of greenhouse gases. Nevertheless, not all the species can be bred as a consequence of their specific temperature and light requirements. Insects can be considered as safe from a microbiological point of view but can contain residues of pesticides and heavy metal. Attention must be paid to the cross-reactions among allergens found within some insect species. Edible insects can be consumed as whole insects but, in order to increase their acceptability, they can be processed into an unrecognisable form. Many inventions concerning insect processing have been patented. The European Union has a specific new Regulation on novel foods that established an authorization procedure to sell insect-based foods unless their safe consumption for longer than 25 years in third countries is demonstrated. Farming insects can offer revenue opportunities mainly in developing countries.

1. Introduction

The growing interest of researchers for edible insects is proven by the high number of scientific publications. The search of "edible insect" keyword in one of the most accessed abstract and citation database (https://www.elsevier.com/solutions/scopus) gave a result of 637 researches from 1975 to 29th January 2020 (Table 1). The first article found in that database dated back to 1973. About 90% of papers have been published starting from 2010. About 11% of papers were published by Italian researchers, followed by Dutch (9.6%), and US (8.9%), scientists. Articles were mainly published by researchers from Europe and Africa. Most of the papers were represented by articles (∼78%), review (∼14%), and book chapter (∼5%). About 24% of the papers were open access. Regarding the subject area, most of papers was classified in the 'Agricultural and Biological Sciences' (∼81%), followed by 'Biochemistry, Genetics, and Molecular Biology' (∼17%), and 'Environmental Sciences' (∼17%).

Due to the consistent number (Table 1) of valuable reviews on edible insects available in literature - the work of Dobermann, Swift, and Field (2017) can be cited as an example - the publication of further similar papers would seem unnecessary. Nevertheless, it would be wrong to ignore the acceleration undergone by basic and applied research activities on edible insects (especially on their safety characteristics) in the last years, as proven by the increasing number of research papers published (+51% between 2017 and 2019; +227% between 2015 and 2019), the long list of entrepreneurial activities involved in edible insect farming and insect-based food production/marketing in the same period (http://tinyurl.com/zyotzcy), and the steady increase in the number of successful crowdfunding campaigns launching new insect products on the market (Shoeckley, Lesnik, Allen, & Fonseca Muñoz, 2018). Based on this statement, the work was aimed to give an updated overview on several edible insect issues, with special

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Table 1
Distribution of papers on edible insects.

Classification of the research paper containing the keyword "edible insect" within Title, Abstract, and Keyword fields		Number of Papers
	1973	1
by Year	1992	1
	1995	2
	1997	9
	1998	2
	1999	2
	2000	2
	2001	2
	2002	4
	2003	4
	2004	1
	2005	1
	2006	5
	2007	2
	2008	7
	2009	18
	2010	7
	2011	13
	2012	9
	2013	25
	2014	20
	2015	45
	2016	68
	2017	97
	2018	125
	2019	147
	2020 (until 29th January)	18
by Country/territory	Italy	72
	Netherlands	61
	USA	57
	China	45
	Germany	43
	South Korea	42
	Mexico	40
	Belgium	39
	Kenya	35
	Denmark	30
	United Kingdom	29
	Uganda	27
	Finland	24
	India	22
	Czech Republic	21
	Thailand	21
	Australia	20
	Japan	20
	South Africa	20
	France	18
	Nigeria	15
	Austria	13
	Cameroon	13
	Brazil	12
	Canada	12
	Zimbabwe	11
	Poland	9
	Ghana	8
	Sweden	8
	Israel	7
	Mali	6
	Switzerland	6
	Hungary	5
	Portugal	5
	Spain	5
	Tanzania	5
	Turkey	5
	Egypt	4
	Pakistan	4
	Angola	3
	Burkina Faso	3
	Ecuador	3
	Laos	3
	Norway	3
	Zambia	3
	Others	49

(*continued on next page*)

Table 1 (*continued*)

Classification of the research paper containing the keyword "edible insect" within Title, Abstract, and Keyword fields		Number of Papers
by Document type	Article	496
	Review	88
	Book chapter	31
	Editorial	8
	Note	5
	Short survey	3
	Book	2
	Conference paper	2
	Erratum	1
	Letter	1
by Access type	Open access	152
	Other	485
by Subject area	Agricultural and Biological Sciences	517
	Biochemistry, Genetics, and Molecular Biology	108
	Environmental Sciences	92
	Engineering	69
	Medicine	68
	Social Sciences	66
	Chemistry	57
	Immunology and Microbiology	44
	Nursing	44
	Pharmacology, Toxicology and Pharmaceutics	23
	Multidisciplinary	15
	Veterinary	14
	Chemical Engineering	12
	Health Professions	12
	Business, Management and Accounting	10
	Earth and Planetary	9
	Economics, Econometrics and Finance	8
	Arts and Humanities	6
	Energy	6
	Psychology	5
	Computer Science	2
	Mathematics	1
	Neuroscience	1
	Physics and Astronomy	1

reference to processing, patents, safety, healthiness, consumer profile and preferences, and sustainability.

2. Edible insects: a brief historical excursion

The use of insects in human nutrition has been practiced since ancient times, even for millions of years (Sponheimer, de Ruiter, Lee-Thorp, & Spath, 2005). Diets rich in insects in hominids such as Australopithecus are proven by high 13C/12C and Sr/Ca ratios measured in their dental enamel. *Australopithecus robustus* used bones sapiens in harvesting termites (Blackwell & d'Errico, 2001). The first "recorded" cases of entomophagy, dated back to 30,000 to 9000 BC, are represented by some cave paintings discovered in Altamira (north Spain) that depict the collections of honeycombs and bee nests (Schabereiter-Gurtner et al., 2002). Most likely, the first humans chose insects to eat by observing the behaviour and diet of animals.

The practice of eating insects is cited throughout religious Christians, Jewish, and Islamic literature (Thakur, Thakur, & Thakur, 2017). In the Old Testament book of Leviticus, the writers included locusts, beetles, and grasshoppers among the foods among the foods whose consumption was allowed. John the Baptist himself survived for months in the desert, feeding on locusts and honeycomb. The ancient Romans and Greeks made meals of beetle larvae and locusts. The ancient Algerians used locusts as foods after having cooked them in salted water and dried in the sun. The Australian aborigines fed on moths previously cooked in the sand and then deprived of wings, legs and head, in order to leave their meat (Bryant, 2008).

Today, insects are consumed in 11 European countries, 14 countries in Oceania, 23 American countries, 29 Asian countries, and 35 African countries. Mexico, China, Thailand, and India are the leading consumer countries and those with the most species (Jongema, 2017). Although it's not the same as consuming insects, in Croatia, maggot cheese is still considered a delicacy and in Italy, the so-called "casu marzu" is a maggot cheese listed in the database of traditional agricultural Italian food products.

One of the most important reasons of the difference in distribution of anthropo-entomophagy around the globe is that not all environments are conducive for producing edible insects. The tropics offer the most insect biodiversity while, as latitude increases away from the tropics, insect eating decreases (Lesnik, 2017). Today, anthropo-entomophagy concerns 2300 insect species and it is practiced by about 3000 ethnic groups in over 100 countries mainly located in Africa and Asia but also in Latin America (van Huis et al., 2013). It is estimated that insects are included in the traditional diets of at least 2 billion people. The most commonly consumed insects are, in a decreasing order: beetles (Coleoptera, 31%); caterpillars (Lepidoptera, 18%); bees, wasps and ants (Hymenoptera, 14%); grasshoppers, locusts, and crickets (Orthoptera, 13%); cicadas, leafhoppers, planthoppers, scale insects and true bugs (Hemiptera, 10%); termites (Isoptera, 3%); dragonflies (Odonata, 3%); flies (Diptera, 2%); others (5%) (Thakur, Thakur, & Thakur, 2017).

Regarding animal feed in Europe, insects such as black soldier fly (*Hermetia illucens*), yellow mealworm (*Tenebrio molitor*), and mealworm (*Alphitobius diaperinus*) constitute the most relevant species used as derived products for farmed animal feed. Instead, larvae from yellow mealworm and lesser mealworm, black soldier fly, wax moth (*Galleria mellonella*), grasshoppers, silk moth (*Bombix mori*), and cricket species are used to produce foods for pets, circus and zoo animals (Derrien & Boccuni, 2018).

3. The reasons for the current and future human consumption of insects

Apart from the traditional use of insects in the feeding of some populations, insects are considered to be as one of the pillars of the future human nutrition for a variety of reasons. First of all, mostly in places where the availability of nutritious foods is lacking, the insect nutritional value must be considered. Factors such as species, development stage, diet, and processing affect the insect nutritional composition (Oonincx & Dierenfeld, 2012). Generally, insects show interesting amounts of high quality proteins since all the essential amino acids are present in the recommended ratios (Belluco et al., 2013; Collavo et al., 2005). Nevertheless, the variability of their nutritional composition must be considered, since it depends on of factors such as: species, development phase, way the insects are killed, and preparation (Van Huis et al., 2013; Paoli et al., 2014; Finke & Dennis, 2014). For example, insects from the taxonomic family of Gryllidae have desired high protein contents (~20 g) and low calories (153 Kcal) but also undesired high amounts of sodium (152 mg) per 100 g of edible portion. On the contrary, insects from Curculionidae have low protein sodium and contents (~10 g and 11 mg, respectively), and high calorie contents (~480 Kcal) (Gere, Zemel, Radványi, & Moskowitz, 2017). Four edible insect species usually consumed in Nigeria (*Imbrasia belina, Rhynchophorus phoenicis, Oryctes rhinoceros, Macrotermes bellicosus*) contain all the essential amino acids (Ekpo, 2011). In most edible insects, the contents of saturated fatty acid ratio is low (less than 40% of the total fatty acids) (De Foliart, 1991) while those of important micronutrients such as iron and zinc is very high (Michaelsen et al., 2009). Vitamin E content is high in insects such as fruit flies (*Drosophila melanogaster*) and false katydids (*Microcentrum rhombifolium*), with values of about 110 mg/kg of dry matter (Oonincx & Dierenfeld, 2012). The type of habitat and diet may affect flavour and nutritive values of insects. As an example, in a study of Oonincx and van der Poel (2011), migratory locusts were fed with three different diets consisting either solely of grass, mixed grass and wheat bran, or combination of grass, wheat bran, and carrots. The wheat bran diets reduced the protein content and increased the fat content, whereas the addition of carrots further enhanced the fat content and provided high levels of β-carotene. Concerning the effects of processing, degutting increases crude protein content and digestibility in mopane caterpillar while toasting and solar drying can decrease protein digestibility and vitamin content of winged termites (*Macrotermes subhylanus*) and grasshopper (*Ruspolia differens*) (Kinyuru, Kenji, Njoroge, & Ayieko, 2010; Madibela, Seitiso, Thema, & Letso, 2007). In China, for 174 of the 324 species of insects that are either edible or associated with entomophagy, the nutritional values are available and, although the data vary among species, all the insects examined contain protein, fat, vitamins and minerals at levels that meet human nutritional requirements (Feng et al., 2018).

The importance of the nutritional value of insects is related to the demand for foods and water of the growing world population. It was expected that the demand for livestock products will double between 2000 and 2050, especially as a consequence of the increasing request for meat products by the population of the developing countries. Livestock rearing is responsible for 14% of the global greenhouse gas emissions (Gerber et al., 2013) and requires a noticeable land use. According to Oonincx and de Boer (2012), to produce 1 kg of edible protein, mealworms required only 10% of the land needed for beef production. Furthermore, edible insects have the advantage to be farmed vertically (van Huis et al., 2013). Livestock rearing also requires large amount of water and this is a dramatic problem since according to FAO Water (2013), by 2025, two-thirds of the world will suffer water shortages. The virtual water content (water used to produce a commodity) of livestock products is very high. In the case of beef, it amounts to 22,000–43,000 L kg^{-1} produced (Chapagain & Hoekstra, 2003) since water is needed for forage and feed production. The virtual water content for edible insect rearing is expected to be much lower since it has been demonstrated that some insects such as the yellow mealworms and the lesser mealworms are drought resistant and can be reared on organic side stream (Ramos-Elorduy, Gonzalez, Hernandez, & Pino, 2002).

Another interesting index is the feed conversion ratio (FCR, expressed as kilogram feed/kilogram live weight). The following FCR data were found in literature: 1.7 for cricket (Collavo et al., 2005), 2.5 for chicken, 5 for pork, and 10 for beef ((Smill, 2002). Since the percentage of edible weight greatly differs between conventional livestock (55% for chicken and pork, 40% for beef) and insects (80%), the FCR corrected for the edible weight shows that crickets (ratio of 2.1) are twice more efficient than chickens, 4 times more efficient than pigs, and 12 times more than cattle (van Huis, 2013). Furthermore, insects grow rapidly and can produce large amount of biomass for food in a short time (Premalatha, Abbasi, Abbasi, & Abbasi, 2011).

All these findings strengthen the idea that insects can help mankind to solve food/protein shortages. Furthermore, a study performed by Mwangi et al. (2018) on 11 edible insect species that are mass-reared and 6 species that are collected from nature highlighted that: the insect levels of Fe and Zn are similar to or higher than in other animal-based food sources; high protein levels in edible insect species are associated with high Fe and Zn levels.

Studies concerning the Life Cycle Assessment (LCA) of edible insects is still limited. Oonincx and de Boer (2012) found that the energy use in mealworm production was higher than in conventional animal products since insect growth and reproduction require temperatures of 20–30 °C. On the contrary, both land use and global warming potential were lower in mealworm production. Furthermore, insects are much easier to grow than large animals. According to Smetana, Schmitt, & Mathys (2019), fresh insect biomass is almost twice more sustainable than fresh chicken meat. The same authors highlighted that, when produced at pilot scale, protein concentrates from insects are competitive against animal-derived (whey, egg protein, fishmeal) and microalgae, but have higher environmental impacts than plant-based meals.

Recapping the environmental advantages of edible insect production, it can be stated that: greenhouse gas and ammonia emissions are negligible, at least in small-scale experiments (Oonincx et al., 2010) and, a part from some exceptions (methanogenic bacteria have been detected in the hindguts of tropical species of cockroaches, termites, and scarab beetles), edible insects are unable to produce methane; the environmental impact is very low over the entire life cycle; insect production is not necessarily a land-based activity; insects are very efficient in converting feed into edible weight; the volume of water required to produce edible insects in equivalent amounts of conventional meat is low (FAO, 2013).

While taking these beneficial aspects into account, researchers should ask themselves whether insects could represent the food of the future. The answer to this question is not so obvious. In fact, although the number of insects living at mid-to-high latitudes is expected to grow with the global warming (Deutsch et al., 2008), the insects tropical living in the ecosystems should decrease by more than 20%. A recent study of Lister and Garcia (2018) confirmed the decline of arthropods (including insects with exoskeleton) at an alarming rate.

4. Safety implications

The increasing introduction of insects in human diet imposes an increasing attention to their safety concerns. As for whatever type of food, the evaluation of the edible insect safety implies the monitoring of harmful microorganisms, parasites, toxins, heavy metals, veterinary drugs, hormones, and pesticide residues (van der Fels-Klerx, Camenzuli, Belluco, Meijer, & Ricci, 2018; Zhao, 2009).

Insects have a specific plethora of viral pathogens, but they must be considered only from an animal health perspective since these viruses are considered safe for humans. Nevertheless, arthropod-borne viruses (arboviruses) are also able to cause diseases such as Dengue, West Nile disease, Rift Valley Fever, Haemorrhagic Fever, and Chikungunya, in humans (Belluco, Mantovani, & Ricci, 2018). In addition, the possibility that some viruses introduced in insect farms by substrate are transferred to humans can't be excluded.

Concerning microbial contamination, the insects could be mechanical or biological vectors of pathogenic micro-organisms but, if properly processed and stored, they can be considered as safe (van Huis et al., 2013). Generally, insect pathogens are specific for invertebrates (there is a large phylogenetic distance between insects, humans and other mammals) and do not concern vertebrates (Eilenberg, Vlak, Nielsen-LeRoux, Cappellozza, & Jensen, 2015; van Huis et al., 2013). Wynants et al. (2019) investigated the occurrence of transmission of *Salmonella* sp. to mealworms (*Tenebrio molitor*), when mealworms are fed with contaminated wheat bran as substrate. They found that the survival of *Salmonella* sp. in larvae and bran depended on the contamination level. It was higher in bran originally contaminated with 7 log cfu/g while, at a starting contamination level of 2 log cfu/g, *Salmonella* sp. was not detected in the larval samples. Authors speculated that the reasons of this behaviour include the competitive exclusion by the endogenous larval microbiota and/or the antibacterial activity of the larvae.

Regarding parasites, in regions where insect consumption is traditional, human autopsies and insect analyses highlighted that trematodes belonging to the family of *Lecithodendridae* and *Plagiorchidae* can be transmitted through the oral route (Chai, Shin, Lee, & Rim, 2009). Insects species such as Blatella germanica and *Periplaneta americana* have been demonstrated to harbour pathogenic protozoa like *Entamoeba histolytica, Giardia lamblia, Toxoplasma* spp. and *Sarcocystis* spp. (Belluco et al., 2018).

Edible insects may be responsible for mycotoxin contamination when handled or stored at sub-optimal conditions. Low levels of aflatoxin B1 were found in the edible stink bug (*Encosternum delegorguei*) stored in recycled grain containers (Musundire, Osuga, Cheseto, Irungu, & Torto, 2016). The transfer of deoxynivalenol from wheat as substrate to mealworm larvae was found when the substrate was spiked with high concentrations of the mycotoxin (van Broekhoven, Gutierrez, de Rijk, de Nijs, & van Loon, 2014).

Feeding substrates for insects may contain environmental contaminants such as heavy metals, chemical elements such as selenium, dioxins and other organochlorines, and polybrominated diphenyl ethers, which can be bioaccumulated (EFSA, 2015). Heavy metals of concern include cadmium in black soldier fly and housefly, and arsenic in yellow mealworm larvae (Charlton et al., 2015); van der Fels-Klerx et al., 2018). The veterinary drug nicarbazin was detected by Charlton et al. (2015) in only one sample of *Musca domestica* grown on poultry manure in. Concerning pesticide residues, Charlton et al. (2015) detected chlorpyrifos in only one sample of *Musca domestica* reared on milk powder and sugar from China, and piperonyl butoxide in only one sample of *Calliphora vomitoria*. The same authors found dioxin-like polychlorinated biphenyls in all of the larvae samples analysed but in concentrations lower than 10 μg/kg.

Insects can be a source of allergens by contact, inhalation, and oral ingestion. For insect species such as grasshoppers and silkworm, it is proven that long-term, high-antigen environmental exposures (this is the case of professional insect farmers), can cause respiratory sensitization in a percentage of up to 50–60% of individuals (Pener, 2014; Uragoda & Wijekoon, 1991). Ji et al. (2009) produced a report of allergies caused by food consumption in China between 1980 and 2007. According to that report, insects were the fourth most common cause of allergies after pineapple, soft-shelled turtles, and crabs. The insects responsible for anaphylactic shock were mainly locusts and grasshoppers, followed by silkworm pupae. Nevertheless, insects were not involved in deaths. According to Broekman et al. (2017), primary sensitization can occur when mealworms are eaten by humans. Nevertheless, the same study highlighted that an allergic reaction to one insect species does not necessarily imply an allergic reaction to all insects.

Cross-reaction among allergens found within insect species is possible. For example, the cross-reaction between house dust mite sensitivity and yellow mealworm proteins such as insect tropomyosin and arginine kinase has been demonstrated (de Gier & Verhoeckx, 2018; Verhoeckx et al., 2014).

Recombinant allergens from insects such as cockroaches, silkworms, and Indian mealmoths are available, thus allowing research on diagnostic allergy tests and vaccine candidates (de Gier & Verhoeckx, 2018).

Health concerns can also be due to chitin, a long-chain polymer of N-acetylglucosamine that is a primary component of the exoskeleton of some insects (EFSA, 2015). Chitin can have ‘anti-nutrient’ properties due to its potential negative effects on protein digestibility (Belluco et al., 2013). Chitin is high in fibre and is generally considered indigestible by humans. Nevertheless, the production of chitinolytic enzymes by bacteria from human gastrointestinal tracts has been proven, and this finding would suggest that chitin can be digested (Rumpold & Schlüter, 2013).

Insects possess defensive mechanisms, including the production of carbon acids, alcohols, aldehydes, and phenols, which can be local irritants or, in the case of alkaloids, steroids, cyanogenic glucosides, (benzo)quinones, and alkenes, able to exert significant systemic effects (Belluco et al., 2018).

Other hazards include choking on exoskeletons and injury from stings, barbs, and other body parts. Possible risks concern the ingestion of insects at inappropriate developmental stages or not correctly prepared. For example, the consumption of grasshoppers and locusts without removing their feet can lead to intestinal blockage (Bouvier, 1945).

Although the large number of scientific publications on edible insects, there is still a limited availability of data on their toxicity. For this reason, Gao, Wang, Xu, Shi, & Xiong (2018) summarized the data on the toxicological characteristics of edible insects in China. They found that only less than 34 insect species, belonging to Lepidoptera, Coleoptera, Orthoptera, Hemiptera, Hymenoptera, Blattodea, Diptera, and Amorphosceloidea, have been assessed by toxicology studies and that these studies are heterogenous (thus difficult to compare). The tolerated doses observed in rats and listed in this review are extremely variable, ranging from > 0.17613 g/kg body weight of the Chinese ground beetle (*Eupolyphaga sinensis*) to > 83 g/kg of the Chinese (oak) tussar moth (*Antheraea pernyi*).

The need for safety of edible insects for food and feed lead to the development and application of specific HACCP procedures (Ramos Fraqueza & da Silva Coutinho Patarata, 2017).

Vandeweyer, Lievens, & Van Campenhout (2015) investigated the microbial quality of the yellow mealworm (*Tenebrio molitor*) and house cricket (*Acheta domesticus*) reared for human consumption on an industrial scale in Belgium and the Netherlands. In mealworms, the microbial counts were in the following ranges: mesophilic 8.3–8.5 log cfu/g; psychrotrophs 5.8–6.5, Enterobacteriaceae 6.8–6.9, lactic acid bacteria 7.4–8.2, yeasts and moulds 4.8–5.3, and aerobic bacterial spores 2.3–4.3. In crickets, the ranges were 8.2–8.4 log cfu/g for mesophiles,

Table 2
Differences between small- and large-scale facilities in the management of several issues of the insect rearing (adapted from Berggren et al., 2018).

Issues	Small-scale facilities	Large-scale facilities
Production destination	Human consumption	Medical purposes; production of pet foods; production of foods for circus and zoo animals; pest control
Feeding, cleaning, and handling	Manual	Automated
Insect health control	Visual inspection	Large screening programs for pathogens
Production stock	Breeding and supplementary animals can be mixed	Breeding and rearing stock must be separated. Little or no input from wild-caught insects is allowed.
Climate control	Limited, in particular in outdoor facilities with open section	Need for advanced climate control systems
Overall management	Flexibility	Great storage, production, and packaging capacity

5.0–5.5 for psychrotrophs, 7.7–8.0 for Enterobacteriaceae, 7.3–7.9 for lactic acid bacteria, 6.0–6.1 for yeast and moulds, and 2.9–4.2 for bacterial spores. *Salmonella* and *Listeria monocytogenes* were not detected. Wynants et al. (2018) analysed the microbial dynamics during an industrial-scale production cycle of lesser mealworms (*Alphitobius diaperinus*) for human consumption. The results suggested that feed strongly contributed to the insect microbial load and that some species show a competitive advantage inside the insect gut and become dominant. After harvesting, blanching significantly reduced most of the larvae most microbial counts, but the aerobic endospores remained at 4.0 log cfu/g. Pathogens such as *Salmonella* spp., *Listeria monocytogenes*, *Bacillus cereus*, and coagulase-positive staphylococci were not detected taphylococci were not detected. Moulds belonging to the *Aspergillus* and *Fusarium* genera were detected.

The research of Murefu, Macheka, Musundire, & Manditsera (2019) must be cited to conclude the discussion on the safety of edible insects. They performed an evaluation of the available literature on safety of edible insects. They found that Europe had the highest number of publications (50.0%) on safety of edible insects, followed by Africa with 28.7%. Another interesting finding was that publications from Europe generally were on safety of reared edible insects while those from the African continent were mainly on safety of wild harvested edible insects.

While the availability of a plethora of articles on the microbiology of edible insects, little is known about the microbiology of processed insect products. Grabowski & Klein (2017) investigated the counts of total bacterial (TBC), Enterobacteriaceae, staphylococci, bacilli, yeasts, moulds, and the presence of salmonellae, *Listeria monocytogenes*, and *Escherichia coli* in 38 samples of insect products processed in different ways: deep-fried and spiced; cooked in soy sauce; dried; powdered; and others. They found that dried and powdered insects (class I) had markedly higher counts than the deep-fried and cooked ones (class II). Microorganisms such as *B. cereus*, coliforms, *Serratia liquefaciens*, *Listeria ivanovii, Mucor* spp., *Aspergillus* spp., *Penicillium* spp., and *Cryptococcus neoformans* were detected in products of class I. All samples were negative for salmonellae, *L. monocytogenes*, *E. coli*, and *Stapyhlococcus aureus*. According to the hygiene criteria for edible insects proposed by Belgium and the Netherlands, class I products failed to comply with many bacterial count limits and should always be consumed after another heating step as indicated by the manufacturer.

A recent study of Vandeweyer et al. (2019) applied a real-time quantitative PCR assessment to detect and quantify relevant transferable antibiotic resistance genes [tet(O, K, M, S) and erm(B)] in fresh edible insects belonging to 2 mealworm species and 2 cricket species. According to the results obtained, mealworms contained higher numbers of tet(K), tet(M), and tet(S) genes than crickets, but tet(O) was almost uniquely present in crickets. The erm(B) gene was only detected in one mealworm sample. Difference in antibiotic resistance profile was detected between mealworms and crickets, but not between different mealworm species or cricket species.

5. Edible insect farming

The term 'minilivestock' identifies insects and other small-sized organisms, which can be husbanded, and gainfully consumed by humans (Abbasi, Abbasi, & Abbasi, 2016). Worldwide, about 92% of edible insects are harvested from the wild (Yen, 2015a) and only small amounts of insects are specially raised. This behaviour could be a source of serious concerns. First of all, quality and safety of insects harvested from the wild cannot be guaranteed. Furthermore, the harvest of insects from the wild may cause the extinction of species (Yen, 2015b) such as the red agave worm (*Comadia redtembacheri* or *Xyleutes redtembacheri*) used in mezcal, the Navajo reservation ant (*Liometopum apiculatum*), and the agave weevil (*Scyphophorus acupunctatus*) (Ramos Elorduy, 2006). On the other hand, not every type of insect can be raised completely in artificial conditions (Feng et al., 2018) and, in any case, pathogen spreading through a captive population remains a problem to consider (Ghazoul, 2006). One example is represented by the *Acheta domesticus* densovirus (AdDNV) that have decimated the commercial rearing of house crickets in Europe and parts of North America (Szelei et al., 2011). Sometimes, the harvest of edible insects could show undoubted advantages. In fact, many edible insects (for example, Orthoptera species such as *Locusta migratoria*; Coleoptera such as *Oryctes rhinoceros*; Lepidoptera such as *Anaphe panda* (Cerritos, 2009) are considered threats to agricultural crops and therefore chemically controlled with pesticides and insecticides. The manual collection of these pests can both saves crops and benefit the environment by reducing the use of pesticides (van Huis et al., 2013).

Insects can be reared and bred for human food and animal feed using two approaches: the insects can be either fully domesticated and reared in captivity or partially raised in captivity, modifying the insect habitat to increase production but, generally, without separating them from their wild populations. Therefore, different farming strategies can be used (Feng et al., 2018). The fully domesticated insects include mealworms, cockroaches, and some beetles. Instead, locusts, wasps, bamboo caterpillars, palm weevil larvae, and dragonflies belong to the second category. The activities surrounding semi-cultivation contribute both to edible insect habitat conservation and food security (van Huis et al., 2013). Manipulation of environment to procure edible insects is considered as a semi-cultivation. Examples of semi-cultivation include: harvesting of edible eggs of aquatic hemipterans from artificial oviposition sites; deliberately cutting of palm trees to trigger egg laying by palm weevils and the subsequent harvesting of larvae (Van Itterbeeck & van Huis, 2012).

Mealworms and cockroaches are ideal candidates to farming (in both home and factory scale) since their rearing conditions have been extensively studied. Some insects (*L. migratoria manilensis*, for example) can be reared in plastic greenhouses. Insects such as wasps, bamboo caterpillars, and dragonflies are not fully domesticated. Some insects can be reared in semi-artificial habitats, taking care to feed them (Feng et al., 2018).

Insects can be sustainably reared on organic side streams (e.g.

manure, pig slurry and compost). Insect such as the black soldier fly (*Hermetica illucens*), the common housefly (*Musca domestica*), and the yellow mealworm (*Tenebrio molitor*) efficiently bio-convert organic waste. According to Veldkamp et al. (2012), these species could collectively convert 1.3 billion tonnes of bio-waste per year.

Insect farming plays an important role in Thailand, where 20,000 farms produce around 7500 tonnes per year (Hanboonsong, Jamjanya, & Durst, 2013). In Thailand but also in Laos and Vietnam, two species are produced - the native cricket (*Gryllus bimaculatus*) and the house cricket (*Acheta domesticus*) – and insects are reared simply in sheds in one's backyard, and there is no need for expensive materials (van Huis et al., 2013). In temperate zones, insect farming is performed by family-run enterprises and concerns insects such as mealworms, crickets, and grasshoppers. These insects are frequently reared in closed spaces, and the climate control is required in order to avoid desiccation of soft-bodied larvae. The industrial farming requires greater knowledge of biology, rearing conditions, and diet formulation (Feng & Chen, 2009).

In January 2012, a meeting entitled 'Expert Consultation Meeting on Assessing the Potential of Insects as Food and Feed in Assuring Food Security' was held to supply recommendations for rearing insects. Topics such as species and strain collection, household and industrial production, safety, health and environmental issues were discussed.

Berggren, Jansson, and Low (2018) published an article focused on the comparison of the two different insect rearing facilities currently in production, namely small-scale rearing and mass rearing. Generally, these two insect rearing facilities have different end products (insects for human consumption and insects for other purposes, respectively). The small-scale enterprises: can be found in developing countries located in south-east Asia as well as in central and southern Africa; are run as family companies or managed by farmer groups and rear insects almost exclusively for the local market (Durst & Hanboonsong, 2015); the insects are locally sourced and eventually supplemented by additional wild-caught individuals (Caparros Medigo, Haubruge, & Francis, 2017). The insect rearing on an industrial scale: are a recent phenomenon and will predominate in the future; are located in western countries (Netherlands, for example) but also in Asia (China and Thailand) (Van Huis, 2013); rely on their own core breeding stock to ensure a great production of insect biomass, thus limiting the possibility of introducing diseases into the system. Table 2 summarizes the differences between small- and large-scale enterprises in the management of the various activities involved in the insect rearing. According to Dobermann et al. (2017), one of the hurdles that prevent the scaling up of insect farming is the identification of ideal insect species for mass rearing. The ideal candidates should have more of the following characteristics: high egg production, high egg hatch, short larval stage, optimum synchronisation of pupation, high weights of larvae or pupae, high productivity, low feed costs, low vulnerability, high-quality protein content.

Information on the most suitable rearing conditions for growth, development and survivorship of each insect species is a prerequisite for mass production technologies. For example, Chia et al. (2018) evaluated the physiological requirements for growth and reproduction of the black soldier fly *Hermetia illucens*. The measured the development rates at 9 constant temperatures (10–42 °C) and fitted them according to temperature-dependent linear and non-linear day-degree models.

Insect farms are rare in the Western countries while the practice of farming insects has been going on in China for over 5000 years (Bessa, Pieterse, Sigge, & Hoffman, 2017). In North America, no farms grew insects specifically for food prior 2012, but there were many farms growing mainly crickets and mealworms to produce feed for pets and fishing bait. Many of the USA and Canadian insect farms have been heavily focused on robotics, mechanization, automation, sensor technology, and data aggregation in order to iterate quickly towards the insect farms of the future (Shoeckley et al., 2018). In Mexico, between 2012 and 2017, there were only few start-up farms working on the domestication of traditionally consumed insects. Actually, there is a network of semi-cultivators and wild-harvesters able to supply chefs, producers, and individual consumers with a variety of insects, especially chapulines grasshoppers and red agave worms (Shoeckley et al., 2018).

Insect cells can be cultured in suspension in a closed bioreactor that operates under controlled conditions with the following advantages: production of insect protein of reproducible quality with the potential for mass production; reduction of the risk of contamination; reduction of the amounts of unwanted components such as chitin; possibility to farm insects in different environments (space included) (Bessa et al., 2017).

In order to get the switch from small-scale to mass production, it is interesting to investigate the possibility to use growing substrates such as food wastes or unusual wild resources. Since one-third of the food produced annually worldwide ends up as waste and most of it is landfilled with important environmental damage, mass rearing of edible insects on food wastes could combine the need to produce always higher amounts of proteins with environmentally friendly procedures. According to a review of Varelas (2019), artificial diets based on food wastes or mixtures of wastes have been tested for black soldier fly, house fly, mealworm, and house cricket mass production with promising results. A non-exhaustive list of the already tested wastes is the following: spent grains and beer yeast; bread and biscuit remains; potato steam peelings; mixture of egg content, hatchery waste, and wheat bran; waste plant tissues; garden waste; catering waste; grocery store food waste after aerobic enzymatic digestion; municipal food waste. Megido et al. (2016) carried out a study aimed to optimise a cheap and residential cricket (*Teleogryllus testaceus*) breeding system based on unused wild resources. Seven unusual diets were based on taro aerial parts, young cassava leaves, young cashew leaves, and brown rice flour (with or without banana slices) were compared to a traditionally used broiler feed diet. The results showed that the diets based on cassava leaves would seem the most promising.

Regarding the collection of wild insects, an article of Tamesse, Kekeunou, Djuideu Tchouamou, and Meupia (2018) highlighted that capture methods in southern Cameroon vary from one insect to another. Manual capture of insects with the hands was principally used for crickets, termites, and cockchafers. The bucket method, consisting of using a bucket with cover to catch and keep an entire colony, was mainly used for capturing honeybees. The period of capture depends on the period of activity of the insects. Those with nocturnal activities like crickets and termites were mainly captured during the night. Honeybees were principally captured at midday while cockchafers were captured in the morning and at midday. Crickets and termites were mainly encountered during the rainy season, while honeybees were mainly encountered during the dry season. Cockchafers were highly encountered in either the rainy or dry season.

6. Preservation/storage of edible insects

As described above, edible insects can be raised but at present they are generally collected in the wild. This means that some of them are available only seasonally and therefore they must to be preserved and stored before processing or consumption. Wasp larvae, weaver ant brood, silkworm pupae, giant water bugs, crickets, and grasshoppers can be preserved by canning. Many other insects are sold alive and shelf life can be improved by refrigeration or by putting them on ice. In the case of fresh insects, freezing (−20 °C) is recommended as a storage method to maintain their microbial quality (Belluco et al., 2013). For dried and powdered edible insects, refrigeration is the best method for avoiding oxidative and microbiological degradation. However, preserving edible insects and their products can be also obtained without the use of the cold chain through techniques such as drying, acidifying, and lactic fermentation (Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012). Also freeze-drying is often practiced to preserve insects. Storage under vacuum and darkness can improve the shelf-life of whole edible

Table 3
List of some of the most relevant patents concerning edible insects published since 2014 (European Patent Office, 2019).

Subject of the patent	Title	Publication number	Publication date
Preservation of edible insects	Preservation process of animal edible insect	CN109965154 (A)	2019-07-05
	Freeze-drying device before processing of edible level insect with unloading function	CN207305997 (U)	2018-05-04
	Drying equipment of edible level insect	CN207335336 (U)	2018-05-08
Production of edible insect-based cosmetics	Cosmetics containing insect cricket protein and herbal extracts for whitening moisturizing and cell regeneration of skin.	KR20190081232 (A)	2019-07-09
	A cosmetic composition comprising edible insect protein	KR20190059715 (A)	2019-05-31
Production of edible insect-based feed	Pet feed composition having enhanced immunity effect comprising extract mixture of edible insect *Acer tegmentosum jujube* and *Hovenia dulcis* as effective component	KR102034492 (B1)	2019-10-21
	Processes for making insects into large quantities of feed	KR20190037061 (A)	2019-04-05
	Nutrition supplement for animal and use thereof	US2019090509 (A1)	2019-03-28
	Lean hog feed and preparation method thereof	CN109349440 (A)	2019-02-19
	Fattening nutrient feed for meat geese	CN108684929 (A)	2018-10-23
	Feed additives for a pet	KR20180103443 (A)	2018-09-19
	Feed composition for pet animal comprising *Gryllus bimaculatus*	KR20180101878 (A)	2018-09-14
	Feed composition for pet animal comprising *Oxya chinensis sinuosa* Mistshenko	KR101985910 (B1); KR20180077893 (A)	2018-07-09
	Feed for fish	CN107981101 (A)	2018-05-04
	Wild chicken feed	CN106819579 (A)	2017-06-13
	Animal nutrition enhancer and application thereof	CN106578356 (A)	2017-04-26
	Crisped grass carp floating pellet feed and preparation method thereof	CN105831487 (A)	2016-08-10
	Dry pet food	CN105614030 (A)	2016-06-01
	Food intake improving fish feed	CN105614027 (A)	2016-06-01
	Pet food composition	CN105613989 (A)	2016-06-01
	Dry cat food	CN105475660 (A)	2016-04-13
	Blue peacock feed	CN104431505 (A)	2015-03-25
	10-40 day-old chick feed and preparation method thereof	CN104472934 (A)	2015-04-01
	5-30 day-old chick feed and preparation method thereof	CN104472933 (A)	2015-04-01
	10-60 day-old chicken feed and preparation method thereof	CN104472927 (A)	2015-04-01
	Yellow-mealworm-containing feed special for laying hens	CN104222657 (A)	2014-12-24
Production of edible insect-based foods	Method for producing high protein bean curd using edible insect	KR20200004161 (A)	2020-01-13
	Preparation method of quick-frozen barbecued bamboo shoots	CN110338377 (A)	2019-10-18
	Rice cake containing edible insect powder and preparing method thereof	KR102060993 (B1); KR20190102698 (A)	2019-09-04
	Method for producing functional healthful soup containing edible insect	KR102020931 (B1)	2019-09-11
	Manufacturing method of nuts bar using edible insects	KR101995745 (B1)	2019-07-03
	Method of using edible insects to produce novel insect tea	CN109907143 (A)	2019-06-21
	Energy bars and a method of manufacturing the same diet that utilizes the edivle insect	KR102035272 (B1); KR20190053613 (A)	2019-05-20
	Making method of health powder food using mealworm	KR20190047180 (A)	2019-05-08
	Method for producing antifreeze protein derived from mealworm and antifreeze protein using them	KR20190048892 (A)	2019-05-09
	Rice noodle manufacturing method and rice noodle using edible insects	KR20190036749 (A)	2019-04-05
	Flavor and consumable compositions	WO2019185514 (A1)	2019-10-03
	Rice cookie using edible insect and method for manufacturing thereof	KR20190021692 (A)	2019-03-06
	Manufacturing method of artificial bean using the edible bug	KR102018197 (B1); KR20190026995 (A)	2019-03-14
	Method for preparing functional rice cake comprising insect powder	KR101966931 (B1); KR20190018898 (A)	2019-02-26
	Insect jerky using edible insect and method for manufacturing thereof	KR20190018813 (A)	2019-02-26
	A method for producing high-protein foods using edible insects	KR101980323 (B1); KR20190005487 (A)	2019-01-16
	Coffee containing edible insect powder and manufacturing method thereof	KR20180134525 (A)	2018-12-19

(*continued on next page*)

Table 3 (*continued*)

Subject of the patent	Title	Publication number	Publication date
	Preparation method of edible dried yellow mealworms	CN109156816 (A)	2019-01-08
	Insect energy rod and processing method thereof	CN109105426 (A)	2019-01-01
	Fermentation and aging food containing edible insects extract	KR102016787 (B1); KR20180133184 (A)	2018-12-13
	edible insect red pepper paste	KR20180124445 (A)	2018-11-21
	Combined heating type insect dryer	KR101920348 (B1)	2018-11-20
	Steamed rice containing extract of medicinal crops and manufacturing thereof	KR101935996 (B1); KR20180126726 (A)	2018-11-28
	Salad dressing composition containing mealworm and manufacturing method thereof	KR101925452 (B1); KR20180121144 (A)	2018-11-07
	edible insect tofu	KR20180117509 (A)	2018-10-29
	Edible insect derived products and processes for the manufacture and use thereof	US2018310591 (A1)	2018-11-01
	Functional meju using larval powder and manufacturing method thereof	KR101917755 (B1); KR20180106746 (A)	2018-10-01
	Functional salted seafood using larva of edible insects Manufacturing method thereof and Health functional foods comprising the same	KR20180106905 (A)	2018-10-01
	Insect distilled spirits	KR20180102357 (A)	2018-09-17
	Manufacturing method of artificial rice comprising the powder of edible insects	KR101892248 (B1)	2018-09-28
	Method and apparatus for manufacturing a molded rice using edible insects	KR101873228 (B1)	2018-08-02
	Emulsion sausages containing edible insect and the preparation method thereof	KR101922547 (B1); KR20180075062 (A)	2018-07-04
	Method for manufacturing boogak comprising edible insects and boogak by the method	KR101927193 (B1); KR20180058146 (A)	2018-05-31
	Tteokgalbi containing edible insect oil and its manufacturing method	KR101942276 (B1); KR20180039510 (A)	2018-04-18
	Rice puffs comprising edible insects and preparation method thereof	KR101845795 (B1)	2018-04-05
	Method for manufacturing wellbeing meat using edible insect	KR20180032797 (A)	2018-04-02
	Manufacturing method for cookie using edible insect and cookie using edible insect manufactured by the same	KR101831896 (B1)	2018-02-26
	Method for manufacturing of chocolates confectionery that contain edible insect	KR20180011685 (A)	2018-02-02
	Manufacturing method for roasted meat using edible insect and roasted meat using edible insect manufactured by the same	KR101827558 (B1)	2018-02-09
	Production method of insect snacks	KR20170134029 (A)	2017-12-06
	The method of Gangjeong with walnuts	KR101797165 (B1)	2017-11-17
	High-protein noodles and production method thereof	CN107348349 (A)	2017-11-17
	Bugs food	KR101944979 (B1); KR20170108631 (A)	2017-09-27
	Preparation made from insect larvaes and method for the production thereof	EP3262958 (A1)	2018-01-03
	Method for producing rice steamed bread comprising edible insect	KR101698330 (B1)	2017-01-20
	A Functional Salt containing eatable insects and it's manufacturing method	KR20170005397 (A)	2017-01-13
	Health food for male fertility	CN106174487 (A)	2016-12-07
	Cellulose health food	CN106174451 (A)	2016-12-07
	Health-care food for female pregnancy preparation	CN106172759 (A)	2016-12-07
	Health-care food	CN106174482 (A)	2016-12-07
	Preparation method of fiber health food	CN106172812 (A)	2016-12-07
	Method for extracting *Tenebrio molitor* oil	CN106118847 (A)	2016-11-16
	Powder soup	KR101725057 (B1); KR20160119996 (A)	2016-10-17
	Mixed powder for making insect noodle	KR101891274 (B1); KR20160118860 (A)	2016-10-12
	Method for preparing cookies comprising edible insect and cookies thereby	KR101627075 (B1)	2016-06-13
	Energy bars and a method of manufacturing the same diet that utilizes the edivle insect	KR101622784 (B1)	2016-05-19
	Preparation method for multi-flavor quick frozen dumplings	CN104621419 (A)	2015-05-20
	Producing method of edible insect, the edible insect and producing method of paste using the edible insect	KR101493916 (B1)	2015-02-17

(*continued on next page*)

Table 3 (*continued*)

Subject of the patent	Title	Publication number	Publication date
	Eatable bug etc specialty buffet shop	KR20140118438 (A)	2014-10-08
Production of edible insect-based medicines	Composition for preventing and treating diabetes and complications	CN109771578 (A)	2019-05-21
	Drink for preventing and improving obesity comprising the extracts from *Ganoderma lucidum* and preparation method thereof	KR20190028413 (A)	2019-03-18
	Preparation method of protein powder kimchi for preventing obesity using edible insects and black garlic	KR101937640 (B1); KR20180127778 (A)	2018-11-30
	Mixed powder and method for manufacturing pill	KR101775377 (B1); KR20170094628 (A)	2017-08-21
Rearing of edible insects	Insect sorter	KR102039803 (B1); KR20190084170 (A)	2019-07-16
	Edible insect of artificial feed manufacture method using red ginseng residue	KR20190066461 (A)	2019-06-13
	KJM2-5 Lactobacillus plantarum KJM2-5 or feedstuff composition comprising the same for *Protaetia brevitarsis seulensis* larva	KR101980805 (B1); KR20190051149 (A)	2019-05-15
	Edible insect breeding device	KR20190021527 (A)	2019-03-06
	a moisture feeding device of insect seed	KR20190012312 (A)	2019-02-11
	Edible insect breeding system and a breeding method thereof	KR20190008497 (A)	2019-01-24
	A feeding device of insect seed	KR102052476 (B1); KR20180137061 (A)	2018-12-27
	Simple and easy edible aphid Cecidomyiia pupa is collected and release	CN208175828 (U)	2018-12-04
	Edible insect action observation system is planted to variable luminous environment	CN208080358 (U)	2018-11-13
	Method for breeding *Omphisa fuscidentalis hampson* rich in various trace elements	CN108157301 (A)	2018-06-15
	Edible level insect rearing cage	CN207322423 (U)	2018-05-08
	Worm's ovum collection system suitable for insect scale is bred	CN207235860 (U)	2018-04-17
	Honeybee breeding method	CN107535438 (A)	2018-01-05
	Piercingsucking mouthparts insect liquid fodder feed rack	CN206658877 (U)	2017-11-24
	Formula insect feeding device is inhaled to thorn	CN206413611 (U)	2017-08-18
	Green and safe insect feed, as well as preparation method and application thereof	CN106954765 (A)	2017-07-18
	Method for cultivating silkworm insect grass by utilizing empty stomach silkworms	CN106818211 (A)	2017-06-13
	Large-scale lethocerus indicus culture method	CN106508817 (A); CN106508817 (B)	2017-03-22
	Medicated edible insect rearing unit	KR20160131452 (A)	2016-11-16
	Eat insect feeding cage of aphid Cecidomyiia	CN205143241 (U)	2016-04-13
	Liquid nutrients's cultivation box is replenished for insect	CN205082492 (U)	2016-03-16

insects even when stored at room temperature by preserving the microbiological quality of the product and preventing lipid oxidation (Ssepuuya, Aringo, Mukisa, & Nakimbugwe, 2016).

Heat treatments are generally able to inactivate bacteria cells but spore-forming bacteria could survive (Klunder, Wolkers-Rooijackers, Korpela, & Nout, 2012).

7. Processing of edible insects

Edible insects can be killed by freeze-drying, sun-drying, and boiling. Then, they can be consumed as whole insects (raw, boiled, boiled and dried, fried, roasted). A survey performed by Adeoye, Alebiosu, Akinyemi, and Adeniran (2014) on the processing means of edible insects in Lagos State showed that the most preferred method for preparation is roasting (62%), followed by frying (28%), and boiling (7%). However, the processing of insects into an unrecognisable form might be useful to persuade also the most sceptical consumers. In this perspective, insects can be peeled, reduced in ground and paste form (drying and grinding). The insect flours can then be used to enrich existing foods such as crisps, bread, pasta, and similar products. Oils, beverages, and confectioneries can also be produced starting from insects.

Melgar-Lalanne, Hernàndez-Àlvarez, & Salinas-Castro (2019) produced a review on conventional and innovative methods/technologies applied in insect processing. Drying of whole edible insects is conventionally obtained through sun-drying, freeze-drying, and oven-drying while freeze-drying and oven-drying are mainly used for insect flours and powders. Microwave-assisted drying, bed-drying, microwave-drying, vacuum-drying, and conventional-hot-drying on a rotating rack caused minor changes in protein, fat, and fibre contents. Traditional and novel techniques have been also tested for protein, fat, and chitin extraction. Insect protein can be extracted using water, organic solvents, and enzymes to facilitate industrial processes but also techniques such as dry fractionation and sonication. Soxhlet extraction, aqueous extraction, and Folch extraction as well as ultrasound-assisted aqueous extraction and supercritical CO_2 extraction can be used to extract oil. The cold atmospheric pressure plasma can be used to produce an insect flour having high quality. However, the costs of the extraction procedures are currently prohibitive (Thakur, Thakur, & Thakur, 2017).

Sometimes, insects are prepared for consumption through complex multi-step processes. For example, in Zambia, caterpillars are: collected; eviscerated, roasted over hot coals until the setae and spine body adornments are burned off and the caterpillars become hard; sun-dried to make them crispy; and packaged in sacks or other material (Mbata, Chidumayo, & Lwatula, 2002). In Kenya, termites and lake flies are processed into conventionally consumed products such as crackers, muffins, sausages, and meat loaf (Ayieko, Oriamo, & Nyambuga, 2010). A spicy Mexican food product made of chickpeas and lesser mealworms was developed for the Dutch market (van Huis, van Gurp, & Dicke, 2012). A spicy, popped snack based on mealworms and cassava has been produced in Europe (van Huis et al., 2013). Another example of promising edible insect product is the protein-enriched sorghum porridge called SOR-Mite, which won the first prize of the "developing solutions for developing countries" competition promoted by the Institute of Food Technologists. That product combined sorghum, notoriously poor in proteins, essential amino-acids, and fats, with the flying termites. Recently, several companies are working on extraction and restructuration of insect proteins into versatile food ingredients, like soluble protein powders for beverages and textured insect proteins for meat analogues, and egg or dairy replacements in baking and food processing applications (Shoeckley et al., 2018). A form of novel technology that has been proposed to develop the edible insect market is 3D printing, since it can alter both the aesthetics and the texture of food (Lupton & Turner, 2018).

As highlighted in a previous paragraph, the production of edible insects is concentrated in household and small-scale enterprises. Nevertheless, the diffusion of edible insects as food and feed requires the availability of large quantities of raw material with standardised quality and productions on larger scale. The scale-up to the industrial processing will be possible only after the development of regulations and guidelines for producers and there will be the necessary conditions to supply products alternative to the traditional ones with the following characteristics: low-cost, high nutritional value, ease of storage, long shelf life (van Huis et al., 2013). Another challenge is represented by the equipment cost and availability. The industrial processing of edible insects is still new and requires substantial capital investments. Sometimes, the necessary equipment does not exist yet and the cost of the design and engineering of suitable equipment is quite high. So far, this challenge has been only met by few plant producers. For example, since early 2018, Bühler Insect Technology Solutions and Alfa Laval join their forces to offer advanced modular insect plant solutions.

8. Patents concerning edible insects

The processing of edible insects has gaining the interest of many inventors and potential applicants. As a consequence, several inventions have been patented and are available in literature. Table 2 provides an overview of some of the most relevant patents published worldwide since 2014 (European Patent Office, 2019). About 54% of the patents listed in Table 3 concern methods for producing edible insect-based foods. The other patents involve methods for producing edible insect-based foods feed (~19%), methods and devices for edible insect rearing/farming (~19%), the use of edible insects in medicine (~3.6%) and cosmetic (~1.8%), production, and methods of preservation of edible insects (~2.7%).

A brief description of some patents concerning the rearing of edible insects and the production of insect-based foods is reported below.

The international patent WO 2015/070194 Al (2015) describes some methods for producing insect-based products. These methods include wet-grinding of at least one whole insect into an insect slurry and drying the insect slurry to form a dried insect product. This patent also provided a method to produce a chitin product through wet-grinding of at least one whole insect into an insect slurry and removing chitin from at least a portion of the insect slurry.

The international patent WO 2017/066880 Al (2008) concerns products derived from edible insects, their processing, and their use. The described process allows to produce an edible protein product derived from at least one insect and includes the following steps: production of an insect milk; combining at the least one insect with an extraction buffer solution containing at least one of a monovalent salt, a divalent salt and a phosphate salt; adjusting of the pH level of the insect milk; heating of the insect milk to coagulate it and form whey and at least one curd.

The Chinese patent CN101117612B (2012) concerns the production of an edible insect oil. The raw materials are represented by insects such as cicadas, mealworms, locusts, and pupae. The production process includes the following steps: selection, trash, detoxification, curing, vacuum freeze drying, crushing, and supercritical carbon dioxide extraction in the vacuum. The resulting oil can have pharmaceutical, food, and cosmetics use. The extraction also supplies protein material and chitosan.

US patent US20180077912A1 (2016) relates to a method for breeding insects that comprises: a synchronisation sequence, during which a batch of insects is sorted and divided into a plurality of size or maturity categories in separate containers; the grouping of said containers to form basic breeding units containing only insects of the same category.

European patent EP 2863762 A1 (2015) provides a method to convert insects or worms into nutrient streams, such as a fat-containing, an aqueous proteinaceous-containing, and a solid-containing fraction. The method comprises the steps of: squashing of insects or worms to obtain a pulp; enzymatic hydrolysis of the pulp and obtaining of a hydrolysed mixture; heating of the hydrolysed mixture to temperatures of 70–100 °C; and application of a physical separation step, preferably consisting in decantion and/or centrifugation. The resulting nutrient streams can be used in food, feed, and pharmaceutical industry.

European patent EP 3078277 A1 (2016) relates to a method for the manufacture of an insect powder having a water activity of less than 0.7 and its use.

The international patent WO/2018/122700 (2018) provides the production method of environmentally friendly chitosan from insects belonging to the Acrididae, Tenebnonidae and Gammaridae families, which are less likely to contain toxic or heavy metal compounds. The chitosan is obtained through: grinding of the insects into a powder form; a pre-treatment step; removal of lipids and soluble proteins; demineralization; deproteinization; depigmentation; deacetylation; and recovery of chitin.

9. Current legal framework

The Codex Alimentarius, which represent an international guideline for food safety, does not consider insects as food. At present, in the Codex Alimentarius, insects are only referred to as "impurities". Regulations strongly differ from country to country and most western countries do not even specifically address insects. This non-standardized legal status across the world represents the biggest hurdle for the edible insect industry since it hinders or slows the growth of a global edible insect market.

In the European Union, the entry into force of the new Regulation 2283/2015 on Novel Foods and its implementing Regulations 2468/2017 and 2469/2017 clarified and harmonized rules concerning edible insects that, until then, have been considered as a 'gray area' from a legal perspective. Nowadays, edible insects are undoubtedly considered as 'novel foods'. In fact, Regulation 2283/2015 specifies that the categories of food that constitute novel foods cover both whole insects and their parts. From January 1, 2018, insects and insect-based products must be authorized before being placed on the market and the procedure takes at least 17 months. Nevertheless, the regulation offers a simplified authorization procedure for novel foods that are new for the European Union markets but have been traditionally used in third countries. In such situation, the food can be commercialised on the basis of a simple notification of the food business operator, provided the possibility to demonstrate that the traditional food is safe (consumption has continued for longer than 25 years in the customary diet of a significant number of people in at least one third country) and that there are no safety concerns raised by EU Member States or EFSA. This notification procedure requires only 5 months.

In the English-speaking markets (i.e. US, UK, Canada, Australia, and New Zealand), edible insects are mostly subject to the approval of their food safety agencies.

In Southeast Asia and South America, despite insects are considered as traditional foods, there is little or no regulation on the production of edible insects.

10. Acceptance and social impact of edible insects

The consumption of insects as foods is affected by factors such as culture and religion. These findings could explain the geographical distribution of insect estimation.

There are two different psychological reactions to insects as a foods: in countries where populations practice entomophagy, insects are considered as a valued source of nutrients; instead, in western cultures, insects are considered as dirty, disgusting, and dangerous (Looy, Dunkel, & Wood, 2014). In Western societies, only 12.8% of males and 6.3% of females were likely to use insects as a substitute for meat (Verbeke, 2015). A study carried out by Rozin, Haidt, McCauley, Dunlop, and Ashmore (1999) on American students highlighted the so-called 'yuck' or 'disgust' factor: those students were available to touch insects with their hand but not with their lips.

Rozin, Chan, & Ruby (2014) elaborated a prediction model of the insect acceptance by American people. That model included demographic and psychological variables such as: disgust sensitivity; beliefs about risks and benefits of consuming insects; desire of new experiences or, on the contrary, food neophobia; gender. Other influential factors seem to be familiarity, interest in the environment, interest in sustainable food consumption, convenience, and attachment to meat (Verbeke 2015). As already highlighted, insect acceptance could be improved by transforming them into more conventional forms (hot dogs or fish sticks types) or by adding extracted and purified insect proteins to conventional foods (van Huis et al., 2013). Barsics, Megido, and Brostaux (2017) carried out an experiment. They administered some bread to a group of tasters providing them with the false information that insect meal was used as an ingredient for its production. As a consequence, the judges attributed very low scores to the bread flavour.

Acceptance of edible insects is also related to their sensory quality (Kouřimská & Adámková, 2016). Insect flavour is affected by the environment where insects live, their feed, and the cooking method. For example, boiling makes the insects tasteless because their pheromones diffuse into the cooking water. Processing also affects the insect colour that changes from the original blue/green/gray to red (with cooking), golden/brown/black (with drying). The insect texture is related to the cooking method but also to the development stage. In fact, the exoskeleton of most adult insects makes them crispy. Although insects are mainly consumed in their pupae, larvae, and nymph stages.

A survey performed by Fischer and Steenbekkers (2018) in Netherlands was aimed to investigate the ways in which consumers, with and without insect tasting experience, were more or less willing to eat different insects. They found that the insects promoted in the market (grasshoppers, crickets, and mealworms) were more preferred than the less promoted ones. Furthermore, a subgroup of preferred insects was formed for participants with experience in eating insects. The four insects that the participants were least willing to eat included wasps, cockroaches, bees, and moths. These results substantially confirmed and combined findings from previous studies on European cases.

Perceptions of risks, benefits, control (regulation and labeling), and potential environmental impact could have a certain importance for consumer acceptance of insects as foods. Halloran and Flore (2018) assess the opinions of 68 aspiring young chefs towards the use of insects in gastronomy. They were supplied with samples of bee larvae prepared in different ways (frozen, sautéed and on top of a tostada) in order to see the difference in the taste of insects subjected to different preparations. Samples of Anty Gin (a gin made with distilled *Formica rufa*) and grasshopper garum were also given to the tasters. Concerning the barriers to the use of insects in gastronomy, the following results were obtained: disgust (47%); lack of knowledge on how to use and prepare insects (21%); inaccessibility to products (15%); prohibitive food safety regulations (10%); association with poverty (3%); high cost and 'other' (2%, respectively). Instead, the most convincing argument for consuming insects included nutritional, environmental, and taste/deliciousness arguments (31, 29, and 29%, respectively).

Certainly, a promising strategy to overcome the reluctance to eat insects is to target children for education in entomophagy (Tranter, 2013). In any case, a more acceptable pathway to introduce insects in the human diet could be the use of insects for animal feed.

According to Adámek, Adámková, Mlček, Borkovcová, and Bednářová (2018), for the Western consumers, the main criterion that determine the choice of an insect-based food is its acceptability. These authors investigated the acceptability of protein and energy bars enriched with cricket flour for consumers from the Czech Republic. The survey showed that edible insect bars are acceptable as a new type of food since more than 80% of consumers are willing to consume them.

Some recent studied concern the possibility to develop prevision models of the consumer willingness to eat insect-based foods. Hartmann and Siegrist (2018) focused their studies on development and validation of the Food Disgust Scale (FDS), a self-report measure that enables the assessment of an individual's emotional disposition to react with disgust to certain food-related stimuli. They developed 8 FDS subscales that represent unique types of food disgust - animal flesh, poor hygiene, human contamination, mold, decaying fruit, fish, decaying vegetables, and living contaminants – founding that of the 8 FDS subscales, those representing food disgust for animal flesh and poor hygiene were able to predict the Swiss consumers acceptance of insects as food. Jensen and Lieberoth (2019) tested the effects of fear of contamination and perceived social eating norms related to entomophagy on the willingness of 189 Danish students to eat insect-containing foods. The statistical analysis revealed that self-reported trait-level Pathogen Disgust and Perceived Infectability did not consistently predict insect eating disgust, willingness to eat insects, or actual insect tasting behaviour while perceived insect eating norm emerged as a significant predictor of insect tasting behaviour.

Lombardi, Vecchio, Borrello, Caracciolo, and Cembalo (2019) analysed the preferences of 200 Italian consumers for 3 insect-based products such as pasta, cookies, and chocolate bars through a non-hypothetical willingness to pay (WTP) elicitation mechanism. The authors also tested the influence of different types of information on consumer choice and the main forces driving consumer preferences for insect-based foods. The results revealed that the 3 different foods generated different results in terms of WTP for conventional and insect-based versions of the products. More specifically, without being provided information, consumers considered insect-based products either equivalent (the same WTP for the two versions of pasta) or weakly inferior (lower WTP in the case of cookies and chocolate). On the contrary, when information on the benefits of insect consumption was provided, WTP increased for all the insect-based products. In fact, Food Neophobia and Beliefs and Attitudes toward insects were shown to have negatively effects on the WTP for insect-based products.

Van Thielen, Vermuyten, Storms, Rumpold, and Van Campenhout (2019) performed a telephone survey to understand the Belgian population acceptance of insect-based foods. They found that: 79% were aware of the fact that insect-based foods can be bought; 11.2% had already eaten insect-based foods; 31.8% had no experience but were willing to try; 57% had no experience or interest. Potential consumers accepted invisible processed mealworms in energy shakes (60.7%), energy bars (59.6%), burgers (59.3%), soup (56.8%), sandwich spreads (56.2%), unfried snacks (56.2%), and fried snacks (52.7%).

Among the future pricing/promotion strategies adopted by South

Korean business owner and government to alleviate consumer disgust, there were the following ones: the decision to rename insects with more appealing, friendly names; the sale of nutrients and functional components extracted from the insect bodies; the potential use of insects as high-end consumer products thanks to the consumer tendency to draw a connection between high price and "healthy" (Han, Shin, Kim, Choi, & Kim, 2017).

An important social implication of insect farming is that, mainly in developing countries, some of the poorest or outcast members of the society can be involved in the gathering, cultivation, processing, and sale of insects. In fact, insects can be easily collected from wild or farmed with minimal technical or capital expenditure (van Huis et al., 2013). In fact, insect harvesting/rearing is a low-tech, low-capital investment option that offers livelihood opportunities for both urban and rural people (Pandey & Poonia, 2018).

Macombe, Le Feon, Aubin, and Maillard (2019) explored the potential social consequences induced in France by industrial scale development of *Tenebrio molitor* production for feed, under several production and marketing assumptions. They imagined two production scenarios: the first involving a medium-scale insect production in which the reproduction farms produced eggs, the fattening farms produced larva, and a cooperative collected fresh larvae and supplies feed for the insects; the second scenario combined production and processing in a single industrial site (integrated biorefinery) to allow an economy of scale and reduce transportation distances. Two market niches were hypothesized for the products of the production scenarios: the first involving feed for laying hen to produce organic eggs; the second concerning feed for farmed trout differentiated by eating insect meal. The social effects were evaluated through the social life cycle analysis. The main positive social effects of the four scenarios derived from job creation, while the effects on other feed-ingredient suppliers were few. Negative effects derived from the allergy risk or employees and potential disturbance to nearby neighborhoods. The two scenarios involving integrated biorefinery showed the risk activists opposed to industrial scale insect production due to environmental or animal-welfare concerns.

11. Economic impact of edible insects

The global edible insect market is dominated by human consumption, followed by animal nutrition, cosmetics, and pharmaceutical (https://www.meticulousresearch.com/edible-insects-market-2023/).

An important economic implication of insect gathering and farming is that they can offer revenue opportunities, either at household level or at industrial-scale. This is mainly true in the developing countries, where there is a concrete demand for edible insects e (van Huis et al., 2013).

When sold at markets, insects achieve prices generally higher than the crops from which they were collected and sometimes higher than conventional fish and meat. The results of the studies of Munke and Owino (van Huis et al., 2013) gave an overview of the insect selling prices in various countries. In Kenya, 1 kg of termites was sold at € 10. In the Netherlands, 50 g of the yellow mealworm and the lesser mealworm cost € 4.85. Also in the Netherlands, it was possible to buy online 35 migratory locusts at around € 10. In the Lao People's Democratic Republic, grasshoppers were sold at € 8–10 per kg. In Cambodia, one can (150–200 g) of fried crickets quoted at € 0.40–0.70. According to Tamesse et al. (2018), in southern Cameroon, the sale of insects allowed daily earning from USD 2–3 for honeybees, to USD 5–10 for termites, and USD 16–20 for cockchafers. Odongo et al. (2018) analysed market opportunities, market players, and value chain of edible insect products in the Lake Victoria basin by collecting data from 147 edible insect traders in Uganda and Burundi. The found that the supply chain for the edible insect *Ruspolia differens* in that area comprised 4 main actors: collectors, wholesalers, retailers, and consumers. The commercial collectors declared that they could collect and sell up to 70 bags (approximately 100 kg each) of the *R. differens* daily during peak swarming season. Each commercial collector received on average of US $ 2696.00 per swarming season. Wholesalers, who usually pack and transport the insects from the points of collection to the points of sale received US$ 2633.00 per season. Retailers added value to *R. differens* insects by frying and packaging them in polythene bags before selling and received on average of US$ 690.80 per season. In the lake Victoria basin, a kilogram of R. differens was sold at about US$ 3.00, vs. US$ 3.50 for beef, and US$ 1.95 for fish.

In developing countries, edible insects are often directly sold to consumers as street foods. The economic impact of these markets is underestimated or neglected (FAO, 2011). The market of edible insects in western countries is driven by demand from migrated communities from Africa and Asia and by the development of niche markets for exotic foods (van Huis et al., 2013).

It is not easy to predict the future of the edible insect market. According to a research report by Global Market Insights (2018), the edible insects market size will surpass USD 710 million by 2024. The analysis by region gave the following results:

- the North America market demand could register growth over 43.5% up to 2024. Crickets are the mostly consumed insects in this region. The edible insect market is favoured by the growing demand for high protein diets and the aversion to processed food;
- the Asia Pacific market (mainly Thailand and China) could surpass USD 270 million by 2024. The mostly consumed insects include: grasshoppers, crickets, beetles and locusts. They are used as dietary food supplements in manufacturing of desserts, smoothies, biscuits and bread due to their high protein content;
- the Europe market is led by Germany and France and should growth at over 43% by 2024. The mostly consumed insects (either as food or feed) are crickets, silkworms, and mealworms.

A report of 2016 estimated that 312 of the 943 million tonnes of protein consumed in 2054 will be represented by alternative proteins (not deriving from meat or seafood) (IKEA, 2016). Insect proteins will be 37 million tonnes.

12. Ethical implications of entomophagy

A recently discussed topic is the welfare of insects reared for food. At present, there is a lack in structured knowledge on how insects should be reared in conditions respectful of their well-being. Breeders manage the various stages of insect production according to generally empirical techniques developed through a process of 'trial and error' (Erens, Es van, Haverkort, Kapsomenou, & Luijben, 2012). It is possible to distinguish 3 schools of thought in ethics: 1) animal welfare advocacy based on the purpose of reducing pains and sufferings; 2) animal rights advocacy, based on ethical rules rather than on their outcome; and 3) pragmatic ethics, based on the social context. The first two schools of thought are abolitionists since they want to abolish human management of animals. This behaviour is a nonsense in the case of animal breeding. Furthermore, the animal welfare advocates use the capacity for suffering and the animal rights advocates use the presence of certain cognitive abilities as groundwork for granting moral status. This means that insects should possess sentience (ability of experiencing pain or suffering) to have the acknowledgment of their right. The followers of the pragmatic ethics are not abolitionists: they acknowledge human management of animals and mainly consider the social context, i.e. the way in which humans interact with animals/insects (Erens et al., 2012).

From an ethical point of view, the legislation on animal protection can be divided into two types: pathocentrically-oriented, which consider only sentient animals, and biocentric, which concerns all animals (Pali-Schöll, Binder, Moens, Polesny, & Monsó, 2018). The present European legislation on animal welfare is based on the so-called

Brambell's Five Freedoms that describe the conditions of animal production. They include: 1) the freedom from hunger and thirst; 2) the freedom from discomfort; 3) the freedom from pain, injury, and disease; 4) the freedom to express normal behaviour; 5) the freedom from fear and distress. According to a scientific opinion of ESFA (2015), the "general animal (vertebrate) health and welfare regulations should also apply for insects". Nevertheless, there is a lack in the European legislation. The same Council Directive 98/58/EC concerning the protection of animals kept for farming purposes excludes any invertebrate animal. If the insect welfare should be considered by legislation, it would have to define the way to use the Brambell's Five Freedoms in relation to insects. For example, the Austrian Animal Protection Act (APA, 2004) established that insects, like any other animals, must not be reared or manipulated in a way that inflicts unnecessary pain, distress or harm on them. According to Hirt, Maisack, and Moritz (2015), the concept of "harm" includes all types of human-induced worsening of the animal conditions, independently on the animal subjective perception.

13. Conclusions

Gathering and farming of insects could represent a promising way to supply other food sources to the increasing world population, in particular in developing countries in Southern and Central Africa and Southeast Asia, where demand for edible insects already exists. Nevertheless, two hurdles should be removed: the non-standardized legal status of edible insects across the world and the aversion of Western population for insect-based foods. From an economic point of view, it is difficult to predict the future of the market of edible insects. It would seem a promising market but it will require financial investments into new processes and new plants to manage insect farming and processing on an industrial scale.

Declaration of competing interest

The authors declare no conflict of interest.

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