Review Article

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The role of edible insects to mitigate challenges for sustainability

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Abstract: This review is focused on the utilization of insects as a new opportunity in food and feed products, including their commercialization both in traditional and new markets. It has been suggested that insects are considerably more sustainable when compared with other sources of animal protein, thus alleviating the pressure over the environment and the planet facing the necessity to feed the world population, constantly increasing. Many chefs have adhered to the trend of using insects in their culinary preparations, bringing insects to the plan of top gastronomy, highlighting their organoleptic qualities allied to a recognized high nutritional value. However, in some markets, insects or insect-based products are not readily accepted because of neophobia and disgust. Moreover, the insect markets, farming, and commercialization are experiencing a huge growth, in which the domain of animal feed is undoubtedly a very strong component. The future of insects as human food and animal feed seems promising in view of the recent trends and challenges.

Keywords: food security, nutrition, insect breeding, animal feed, gastronomy

1 Introduction

According to the statistics of the United Nations, in the past decades a very rapid increase in the world population has been observed. From the Second World War, in the 1940's last century, every 12–15 years an increase of 1 billion people was observed. From 1950 to the present, there has been an increase of over 250%, from 2.6 billion to around 7 billion. According to the United Nations population projections, by year 2050 it is expected that the world population reaches approximately 10 billion (Population 2020).

Although it might be debatable, according to O'Neill et al. (2018), none of the countries in the world is presently able to meet the critical needs for human well-being and at the same time coping with environmental preservation standards. Today's food system is raising key problems not only to the environment and the sustainability goals but also to the overall human health (O'Neill et al. 2018).

Climate change and the Sustainable Development Goals formulated by the United Nations as pivotal to meet by the year 2030 constantly remind of the growing interest in achieving food and nutrition security, especially the goal numbers 2 – Erase Hunger, 3 – Establish Good Health and Well-Being, 14 – Develop Life Below Water, and 15 – Advance Life On Land (Lampe et al. 2014; Meijl et al. 2018, 2020).

Several authors (Rumpold and Schlüter 2013; Baiano 2020; La Barbera et al. 2020) highlighted that the consumption of insects as unconventional or additional sources of animal protein can effectively have many advantages. Firstly, from the nutritional point of view, a wide variety of edible insects presents exceptional nutritive properties (Cappelli et al. 2020b,c). Secondly, insect production has a much lower impact over the environment when compared with other sources of animal protein, including lower emissions of gases with greenhouse effect, lower need of land, more rational use of energy, and reduced needs of freshwater. Finally, insects can be cultivated in much smaller spaces and insect farms can constitute an opportunity for the livelihood of poor families (Rumpold and Schlüter 2013; Baiano 2020; Gahukar 2020; La Barbera et al. 2020).

It has been pointed out in several studies (Payne et al. 2016) that, regarding the nutritional value, insects and traditional meats show little if any difference, despite

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the variability within each category. The authors further conclude that in some cases insects could eventually aggravate some health conditions linked with over-nutrition, while being allies to fight under-nutrition.

According to Cappelli et al. (2020b), insects could bring substantial risks for the safety of not only the consumers but also the workers along the insect production chain. Among these threats stand the possible microbial contamination as well as accumulation and production of chemical contaminants such as toxins and heavy metals. In addition, some people may have allergic reactions, for example, consumers when ingesting insects or workers through inhalation (Cappelli et al. 2020b).

2 Food security

The huge growing of the human population generates several challenges related to food production, food availability, land use, resources management, and environmental impacts. Back in 1975, Meyer-Rochow (1975) discusses the problem of food security and how to feed the world population. According to some, there is enough food being produced in the world, and if it was distributed evenly, starvation and undernutrition would be vanished. However, this theoretical supposition is unrealistic to put in practice for a wide range of factors. This author believed that eating insects could ease the hazards of malnutrition in several countries, particularly those where insects were already part of the culinary tradition (Cappelli et al. 2020b).

Tamburino et al. (2020) have discussed the approaches in scientific literature on the vigorously debated problem of how to feed the world. There seems to be an increasing focus on food production by means of new innovative technologies. In fact, the climate changes have a high impact on primary production and, consequently, on agricultural and animal farming, as well as in fisheries. In addition, at present agriculture continues to depend strongly on fossil fuels, which leads to questioning about the input/output balance in food production (Huang et al. 2020; Sarkar et al. 2020).

Between 1945 and 1994, the energy expenditure in agriculture has increased four-fold, but this resulted in a lower increase in crops yields (only three-fold). Moreover, the use of energy in agriculture has been increasing since 1994, whereas the crop yields have not accompanied that increasing trend, thus corresponding to some degree of inefficient usage of energy (Pimentel and Burgess 2018).

One of the ultimate challenges of the twenty-first century is to produce food in the needed quantities to feed the human population with minimal environmental impacts and maintaining healthy ecosystems (Pimentel and Burgess 2018; Guiné et al. 2020c).

3 Sustainability challenges

Food systems incorporate the complete range of players and their interconnected activities associated with the different phases of the production, processing, distribution, preparation, consumption, and disposal of food, including all the results of those activities, for example, socioeconomic effects and environmental impacts (Recchia et al. 2019). By definition, a sustainable food system is one that guarantees food security and nutrition for all people, while guaranteeing the financial, social, and ecological pillars to provide food security and nutrition for the generations to come (Kawabata et al. 2020).

The world beef production has expanded and is still expanding, much owing to the devastation of tropical rain forests to transform them into pastures for cattle, in a number of countries in South America. Although some attribute livestock a great degree of blame for the increase in greenhouse gas (GHG) emissions (Kruska et al. 2003; Charlton and Rutter 2017; Adegbeye et al. 2019), in other statements the livestock seems to be much more efficient in terms of environmental pressures (Recchia et al. 2019). There is evidence according to which range livestock production is much more efficient regarding environmental and energy issues, when compared with all other systems of food production based on land. This is far from being consensual, and the effects on the environment are still raising, regardless of this discussion (Kruska et al. 2003; Charlton and Rutter 2017; Adegbeye et al. 2019).

Nevertheless, it is still important to eliminate the oil dependence through development of other sources of energy, considered cleaner and cheaper, complementing with high energy, nutritive feed, to make again range/farming livestock production as a fundamental part in providing the meet to face the world's needs (Cappelli et al. 2020a). Precision livestock farming seems to bring new highlights to this problematic and is spreading worldwide in livestock farms, either in intensive or extensive production systems. The livestock production relies on grains, grassland, and crop roughages to provide animal feed, but the utilization of insects in animal feed is already a reality with a very promising future (Fournel et al. 2017; Lovarelli et al. 2020).

In recent years, the demand for alternative protein sources, more sustainable from an environmental point of view, has significantly increased (Cappelli et al. 2020c). Consumers in western countries usually consume higher amounts of protein when compared to consumers in underdeveloped countries, with the highest proportion being from animal origin. Livestock production has a considerable impact on loss of biodiversity, with consequent biosystems' impoverishment; reduction of available freshwater, need for all forms of live on Earth; climate change, and most especially the global warming caused by GHG effect; among others, like animal welfare (Aiking 2011; Huis et al. 2013).

Insect production has been reported as having a lower environmental impact than other sources of animal protein, such as beef, pork, or chicken meats. Among these advantages are lower GHG emissions, the need of much lower areas of land for their rearing, a higher efficiency in the utilization of energy, and much lower inputs of feed and water (Rumpold and Schlüter 2013; Baiano 2020; Gahukar 2020; La Barbera et al. 2020). Nevertheless, some problems can also be pointed out, such as those related to the costs associated with heating the insect production sites in temperate climate countries, control of pests and diseases, or maintenance of hygiene, which have been shown to considerably reduce the attractiveness of food insect farming. Despite this, it is consensual that insects require considerably less feed, space, and water as compared with other animal sources of protein (Finke 2002; Huis 2013; Cappelli et al. 2020b).

4 Insect production

The term "minilivestock" sometimes also called "six-legged livestock" corresponds not only to insects but also to other small organisms, which can be produced for profitability through sale for consumption by humans or to feed animals. In 2015, Yen (2015) reported an estimation according to which globally nearly 92% of edible insect species were collected directly from the wild while only a smaller part was specially reared. Nevertheless, the number of insect farms and volume of production have significantly increased. Insects can be produced using two systems: (1) they are entirely domesticated and cultivated in captivity and (2) they are partly grown in captivity, maintaining them joined with their wild populations, but adjusting the habitat to increase production (Tabassum-Abbasi et al. 2016; Feng et al. 2018; Ghosh et al. 2018; Pongener et al. 2019; Baiano 2020).

It is important to know how to start and scale up insect production farms. Although this is a present and exciting theme, it is also very challenging and still a considerable amount of research is needed to help answering some basic queries, such as those related to consumer acceptance; the type of market addressed and the market's response to the selling price; or processing, conservation, and packaging possibilities. When farmers need to decide which insect to produce, they need to search for the right match between insect and market, and this implies knowing if people already consume that insect, how they consume it, where and under which circumstances. In case there is still no consumption of that insect, farmers need to know whether people will even consider eating it, which can be accomplished through market research. Farmers need to ensure, on the one hand, that they will produce an insect that people are open to eat and purchase, and, on the other hand, they will produce on a large scale in a cost-efficient way. Possible psychological and cultural barriers must be overcome, and innovation plays an important part in the marketing of these types of product (Tabassum-Abbasi et al. 2016; Pongener et al. 2019; Baiano 2020).

4.1 Environmental impact

It is estimated that around 80% of the GHG emissions caused by the agricultural sector comes from livestock production on a broad sense, which includes the emissions originating in land used for foraging, from the energy used to grow cereals for animal feed, and also from the transportation of feed and meat to the processing companies and to the sales players (McMichael et al. 2007). In view of this, alternative approaches rely on insect-based protein supply because of the minored environmental impact of insect breeding. This is so because insects possess single physiological characteristics and biological structures, which allow high efficiency in the conversion of protein into animal protein and also feed energy into food energy, when compared to traditional livestock species. Because insects are poikilothermic (i.e., their internal temperature varies considerably), their metabolism does not need to supply energy to maintain their body temperature, contrarily to homeothermic animals (hot-blooded). This is the reason why the feed conversion ratio (FCR) sometimes designated by feed conversion efficiency (FCE) is considerably higher. FCRs vary considerably depending on the class of animal and the particular conditions of each meat production.

Nevertheless, estimations based on the statistics for the United States indicate that the FCRs for traditional meat production systems are 10 for beef, 5 for pork, and 2.5 for chicken, whereas the FCRs for edible insects are comparatively lower, around 1. Figure 1 shows, as an example, the comparative input/output balance for beef and cricket production, showing that to obtain 1 kg of beef the consumption is 3,000 times more water, 12.5 times more feed, and the necessary areas for husbandry are much higher, when compared with crickets (Smil 2002; Ramos-Elorduy 2008; Nelson et al. 2009; Huis 2013; Huis et al. 2013; Halloran et al. 2016).

Rearing edible insects create lower impacts on the environment when compared to producing other animal proteins. The environmental impacts of insect production, considering feed conversion, land use, and water spending, are incredibly lower than for other types of animals, specifically poultry, pig, and cattle, as indicated in the graphs in Figure 2. The graphs compare the amounts of feed, land, and water required to produce an equivalent amount of insect, chicken, pig, and beef. Insects require the least, followed by chicken, pig, and cow for feed, land, and water usage. Comparatively, cows require over five times more feed, land, and water than insects. It is also taken into consideration the fraction of edible mass, which varies significantly amid conventional livestock and insects. Calculations for protein efficiency indicate that beef, pork, and poultry have values of 190, 150, and 200 g protein/kg of edible mass, respectively, whereas in the case of cricket the values are 154 and 205 g/kg, respectively, for nymphs and adults (Finke 2002; Huis 2013).

The use of insects as food and animal feed appears as a very interesting choice from the perspective of environmental impact in comparison to the usual and more conventional sources of animal protein. The quantification of this impact is currently made through life cycle assessment (LCA) calculations. Halloran et al. (2016) suggested a versatile reference framework for LCA applications in systems for insect production, based on the selection of standardized settings.

4.2 Economic and social impact of the market of edible insects

Over the 5-year period from 2018 to 2023, the edible insect market is expected to grow from about $400 million in 2018 to almost $1.2 billion in 2023 (Figure 3), corresponding to an increase of about 25% per year. Further ahead predictions indicate that this market might be worth around $8 billion by 2030. Although Asia-Pacific and Latin America account for over 50% of the market, it is expected that strongest increases might happen in North America and Europe (Goldstein 2018; Bombe 2019).

The market of edible insects in Asia Pacific area is expected to exceed $270 million by 2024. In Cambodia, insect farming is becoming a key factor to fight against rural poverty. Family farmers and poor families are upscaling cricket production, thus improving their livelihoods. One can with 150–200 g of fried crickets is worth between 0.40 and 0.70 €.

Thailand, where many people enjoy eating a wide variety of insects, leads the world production of insects aimed at human consumption. In recent years, the annual insect production is 7,500 tons, originating mostly from small family enterprises spread all over the country, thus

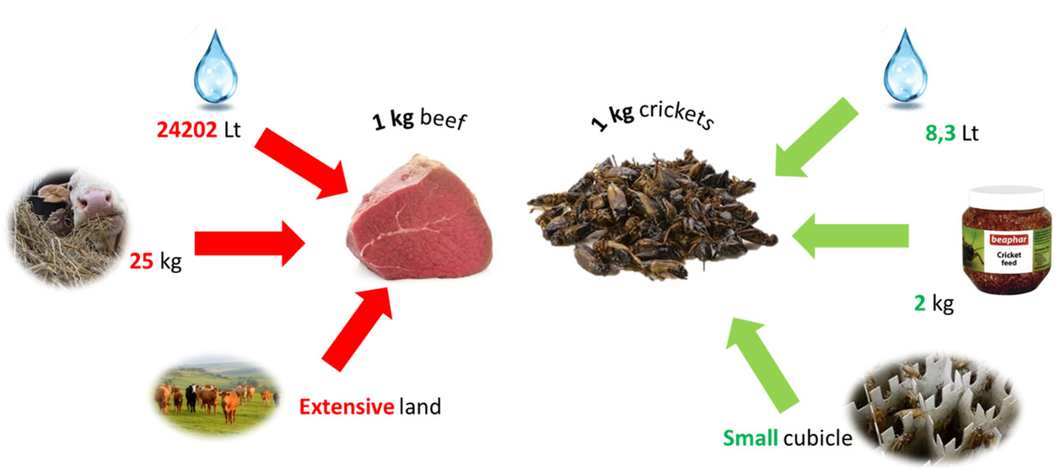

Figure 1: Comparative input/output balance in beef and cricket production.

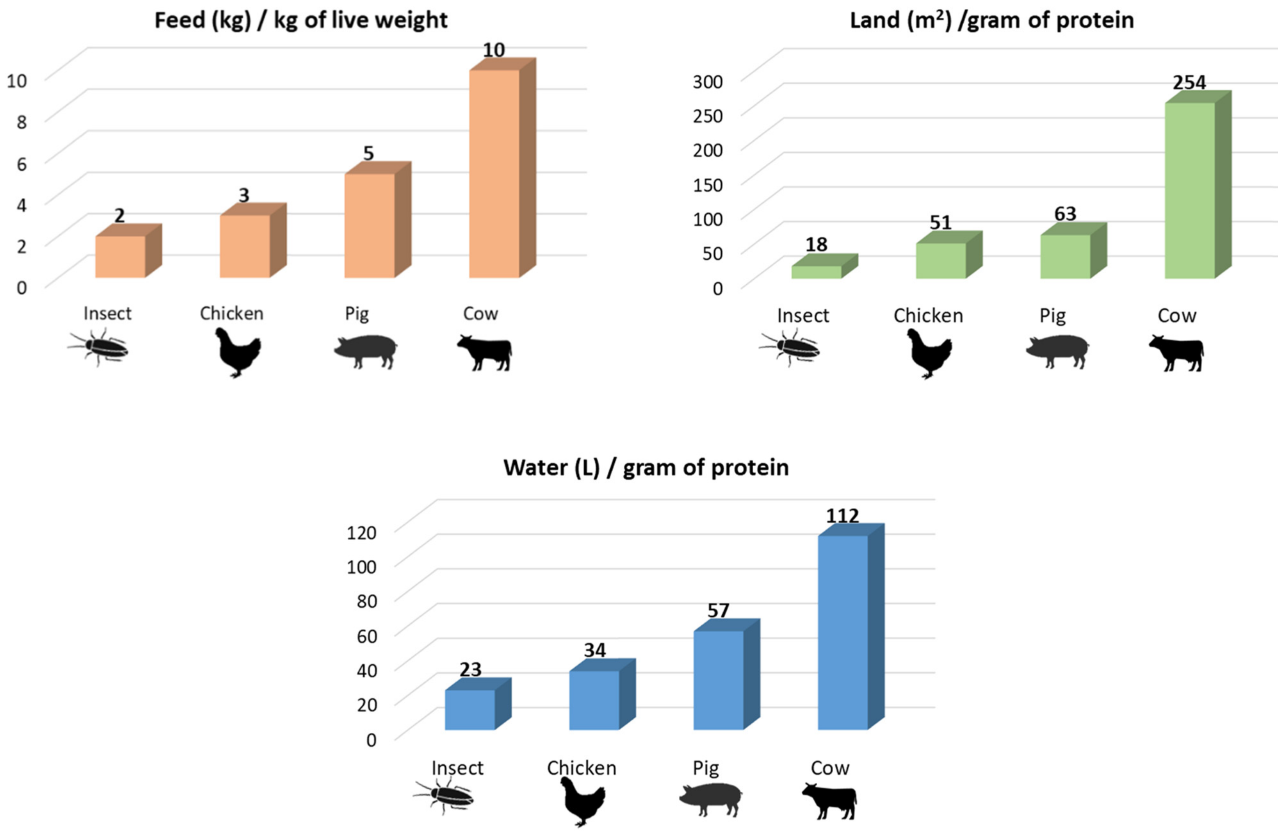

Figure 2: Some measures of environmental impact of animal production, according to the species.

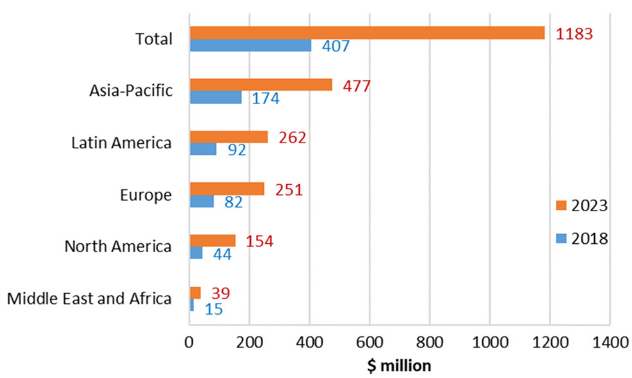

Figure 3: Expected growth of edible insects' market value according to the different regions.

generating a multimillion-dollar industry. The insect production is actually saving poor Thai farmers, generating income and providing a means of livelihood to families. There are over 20,000 listed farms in Thailand, most of them small-scale household operations. Many of them breed crickets, which grow very fast, take up little space and with minimal work (Hanboonsong et al. 2013; Takoradee 2019). On the contrary, Mueller (2019) reported recently a decreasing trend in the insect-eating traditions in Laos and Thailand, owing to the "Westernization" of their dietary habits. This is particularly intense in rural areas, because in urban areas there seems to be some revivalism of the insect-eating practices. Therefore, despite the growing global interest in using insects as human food, some issues still need to be analysed (Mueller 2019). Meyer-Rochow et al. (2008) reported that in Laos people do not have insect in high consideration, seeing them as inconvenient and carriers of disease.

Besides the food and feed markets, also other possibilities are linked with the insect production. In China, recently, cockroach farming has flourished, with some entrepreneurs becoming wealth by selling dried cockroaches for processing into cosmetics and traditional medicines.

In South Korea, the silkworm pupae are a by-product of the silk industry, but because they are edible they have been used as food since many centuries back. On the contrary, edible crickets are much more recent, being reared and consumed for only about 20 years now. Despite being more recent, cricket farming has potential to grow, because the demand for cricket flour is increasing because of its utilization as protein-rich additive in the baking industry (Meyer-Rochow et al. 2019; Cappelli et al. 2020c). As reported in 2019 by Meyer-Rochow et al. (2019), the quantity crickets produced in Korea is muffled by the production of silkworm pupae (10 tons of silkworm pupae are grown per year, from which only 20% are aimed at the market of food and feed).

In many African countries, such as Kenya, Cameron, Uganda, and Burundi, insects provide earnings for many people along the edible insect supply chain, including farmers, collectors, wholesalers, and retailers (Odongo et al. 2018; Tamesse et al. 2018; Baiano 2020). Odongo et al. (2018) studied the edible insects market in the basin of Lake Victoria (areas included in Uganda and Burundi). Their results indicated that edible insects were traded mostly on urban areas, being considered as treats. In addition, they postulate that this market has the potential to increase because of the increasing demand, because at present the demand largely surpasses the offer, which leads to an increase in the prices of insects as compared with beef, pork, or poultry (Odongo et al. 2018).

Tamesse et al. (2018) investigated the importance of certain key insects in Cameroon (honeybees, crickets, cockchafers, and termites) for local villagers. Their results have shown that most people (around 3/4) eat insects and allowed identifying the most consumed as being termites and crickets and the least as being honeybees, because of fear of their venom. Besides their use as food, people in Cameroon also use them in folk medicine, cultural rites, and indigenous traditions (Tamesse et al. 2018).

5 Insects for animal feed

The increasing world population and demand for food, including that from animal origin, indirectly impact the market of animal feed, and it is expected that the worldwide market of feed remains increasing in the future. However, this raise in the need for feed ingredients will impose pressure to the limited natural resources such as land, water, and energy. Escalation of the animal feed market will involve additional policies to address sustainability issues. The utilization of insects in commercial formulas for animal feed represents a possible way to turn animal diets into more sustainable systems, because insects can constitute a better source of protein when compared with the present commonly used sources, with higher environmental impacts (Gasco et al. 2020).

When formulating animal diets, not only the nutritive value of ingredients is a primary concern to cover the animal's requirements, but also the digestibility is pivotal for the well-being of the animal. These diets are optimized based on nutritional criteria allied to performances and costs. Amongst the materials used as ingredients in compound feeds, the proteins are recognized as the utmost important while being also the most expensive. Feed ingredients from animal origin contain easily digestible proteins with high biological value and amino acid profiles. Insects have demonstrated as sustainable suppliers of high-quality nutrients for animal feeds, including protein and fat, and also other macro- and micronutrients (Koutsos et al. 2019; Gasco et al. 2019, 2020).

Awareness is raised about the possible risks associated with insects, because they could, under certain circumstances, serve as carrier vehicles for pathogens and parasites. In addition, some can be venomous and in some cases indigestible. Grabowski and Klein (2017) review possible hazards associated with the use of insects, and they conclude that their consumption in raw state might be problematic. However, most risks might be mitigated by processing technologies used in animal feed formulation, most especially those involving heat treatment, because heat has the potential to destroy some microorganisms, although not necessary eliminating venoms, for instance.

The latest insights and trends in using insects for animal diets show that it is expected that the market of edible insects for animal feed can extend to $2,386 million by the end of 2029. Some companies are pioneers and have already started processing insects in compound feed. In 2018, some companies have invested strongly on the production of edible insects for animal feed (PROTIX – the Netherlands, AgriProtein – the United Kingdom, Ynsect – France, and INNOVA – France). Other key companies in the international market of edible insects for animal feed are EnviroFlight, LLC, Entomo Farms and Beta Hatch in the United States, Enterra Feed Corporation in Canada, NextProtein and Mutatec in France, Entomotech in Spain, DeliBugs in the United Kingdom, Hexafly Biotech in Ireland, Kreca Ento-Feed BV in the Netherlands, Nusect in Belgium, HiProMine in Poland, Haocheng Mealworms Inc in China, Nutrition Technologies and Protenga in Malaysia, and Entobel in Vietnam.

6 Insects: From tradition to novel food

6.1 Insects as ethnic food

In some populations, insects are considered a delicacy. Insects like grasshoppers, cockroaches, larvae, among others are consumed because of their rich protein content, attractive crunchiness, and appreciated taste. Nevertheless, there are important obstacles to consumers' acceptance of edible insects and foods with ingredients derived from insects, especially in western countries. In this way, although entomophagy is naturally recognized in some countries around the world, most especially in Africa, Asia, and South or Central America, it is also true that it is not fully accepted or understood by westerners. Disgust and neophobia were identified as chief psychological barriers averting the consumption of insects (Payne et al. 2016; Verneau et al. 2016; La Barbera et al. 2020).

Insects are consumed by over 2 billion people (Baiano 2020). More than 2,000 species of insects (2,140, as reported) are recognized as being consumed by more than 3,000 ethnic groups in up to 130 countries, concentrated mostly in sub-Saharan Africa, central and south America, or in the southeast Asia and the Pacific. The countries with the highest consumption of insects as food include: Democratic Republic of the Congo, Congo, Central African Republic, Cameroon, Uganda, Zambia, Zimbabwe, Nigeria, and South Africa. Nevertheless, there are 11 countries in Europe which are entomophagous (Ramos-Elorduy 2009; Mitsuhashi 2017; Gahukar 2020; Hwang and Choe 2020).

The most frequently consumed insects comprise crickets, caterpillars, palm weevils, and termites. About 200 types of edible insects are consumed in the southeastern part of Asia. In India, Ayekpam et al. (2014) documented 46 insect species which are used as food among various tribes in Manipur. The Muria tribes in Madhya Pradesh state traditionally consume some species of ants and also an insect known as chin kara. According to some authors, an ancient practice of entomophagy is also present among the people of the Ao-Naga tribe, which populate the district of Mokokchung in the Indian state of Nagaland (Firake et al. 2019; Pongener et al. 2019; Johnson 2020). According to Mozhui et al. (2020), entomophagy is very common in the Nagaland, whose ethnic groups eat a variety of insect species as healthy foods after cooking or raw.

Honeypot ants, with a very prominent belly (swelling to the size of grape berries) filled with a particular nectar, are consumed raw as sweet delicacies by the aborigine peoples in Australia. The huhu beetle grub, similar to big maggot, is eaten as uncooked snack or sautéed as a singular meal in New Zealand, where it is considered a delicacy. Palm weevil larva is eaten in Nigeria, Papua New Guinea, and Malaysia. Wasp larva is eaten as a crunchy snack in some areas of Japan, cooked in sugar and soy sauce, and sometimes mixed with cooked adult wasps. Dragonfly is eaten in Indonesia, boiled or fried as a special treat. Scorpion is eaten in Vietnam, Thailand, and China, boiled or fried as a special treat. Silkworms, known as Nhon Mhai, are the preferred Thailand insect food, principally when fried, being a very popular snack for locals. Water bugs are also eaten in Thailand, where they are very popular, being frequently found in the small street stands in Bangkok. They are consumed in one piece, after cooking by streaming or frying with a spicy sauce. In addition, they are found roasted or canned for consumption by locals (Redford 1987; Melo-Ruíz et al. 2016).

Eating insects is very popular in Chinese culture, where they have been consumed for more than 2000 years. At present, 324 species of insects from 11 orders are documented as being edible or they are associated with entomophagy in China, but the number of edible insects continues to rise as a consequence of more scientific papers that are being published. Insects are frequently consumed at home or in restaurants all year round. Local restaurants regularly serve edible insects such as locusts, ants, silkworm pupae, bamboo insects, termites, Chinese caterpillar fungus, bees, and wasp larvae (Hu and Zha 2009; Feng et al. 2016, 2018).

In Mexico, some native peoples have been using insects as food for very long ages. The Jumil Festival is a Mexican celebration in which people harvest stinkbugs in the woods to consume them raw or alternatively grounded and mixed with chiles to fill tacos. Stinkbug owes its name to the stink it releases and therefore needs a preparation before being fit for consumption, by soaking in warm water. It is rich in vitamin C and is traditionally eaten in Mexico and Southern Africa. Presently, 535 types of edible insects are used in Mexico, in regions situated in the centre, south, and southeast parts of the country. For example, the natives of Los Reyes Metzontla eat 17 different types of insects, at least. Some species of insects are highly valued as delicacies for Mexicans, having a high demand in markets and urban centres. "Chapulines" (grasshoppers of the genus Sphenarium) are among those insects, being consumed roasted to a crunchy texture and mixed with lime and chile, being bought at street stands or alternatively in markets in Oaxaca. In Mexico, some people eat the so-called "insect caviar," which corresponds to eggs of a giant ant (the black Liometopum). These eggs are consumed in tacos, after boiling or frying in butter. Alternatively, they are consumed with tortillas in escamoles, which is also a traditional dish (Ramos-Elorduy 2006; Ramos-Elorduy et al. 2006; Acuña et al. 2011).

The leafcutter ant *Atta laevigata* is traditionally consumed toasted, similar to popcorn or peanuts, in some parts of Colombia and in the northeast Brazil. In the State of Bahia, as in the whole North and Northeast of Brazil, the "coco-bugs" (several families of Coleoptera) are amid the most popular insects among indigenous. People in rural areas obtain these larvae by breaking the coconuts, and these insects, when well fried, are a popular dish among farmers, although many people appreciate them raw. The Suruí Indians, from the Aripuanã Indigenous Park, in Rondônia, Brazil, consume Bruchidae larvae of the species *Pachymerus cardo* F. and *Caryobruchus* sp., called "Kadeg" and obtained from the coconut of the Babaçu palm. They can be consumed raw or roasted in its own fat. Fried larvae are highly appreciated as an accompaniment to roasted corn or popcorn. The Yanomamo of Brazil and Venezuela extract and prepare the larvae of Bruchidae that infest the fallen fruits of the palms. In Manaus, Amazonas, Brazil, at the Jungle Warfare Instruction Center (CIGS) of the Brazilian army, soldiers consume Bruchidae larvae present on fruits of various native palms during jungle survival exercises (Ramos-Elorduy et al. 2006).

Tarantula spiders, although technically arachnids, are compared with insects in relation to eating, being consumed in Latin America (Cambodia and Venezuela). They are usually fried in oil and salted or sweetened with sugar, but sometimes other condiments, like garlic, are used to intensify taste. They have a crispy texture and are traditionally sold in the streets of Cambodia. The indigenous Piaroa people, living in Venezuelan jungles, consume roasted goliath bird-eating tarantulas, which can grow as much as 20 cm diameter (Yen and Ro 2013).

In Africa, stinkbugs are decapitated and pressed so as to empty a gland, and after they are cooked and dried in the sun, to prepare an appetizing snack. In southern Africa, in countries such as Botswana, Zimbabwe, or South Africa, the mopani or mopane worm (the moth Gonimbrasia belina's large caterpillar) is very common and constitutes a good source of food protein. Termites are popular in Australia, West Africa, and some parts of South America, being consumed uncooked, as appetizing snacks, or after preparation, roasted or fried (Redford 1987; Latham 2015).

Meyer-Rochow (2005) presents some cultural roots of practices linked with insect and spider consumption in some ethnic groups of some regions (Northeast India, Papua New Guinea, Australia, and New Zealand). In addition, the reasons for consumption of these foods were addressed. In India, the type of insects consumed varies according to geographical region and is also associated with climate. In Australia, insects are eaten by some aborigine tribe, also varying according to geographical location. In New Zealand, insects are reported as a traditional food for the Maoris ethnic group, whereas in Papua New Guinea people regularly consume a variety of insects and spiders.

6.2 Consumers' acceptance of insects and insect-based foods

Insect consumption, especially for individuals in many western societies, is still interpreted as a taboo (Sidali et al. 2019). Although they represent an interesting source of high-quality nutrients, insects can provoke some adverse reactions, even disgust, besides being considered as a primitive feeding practice. Nevertheless, in recent years some changes have been observed in the recognition and acceptance of insect-based foods. In particular, the sensory characteristics are important for consumer acceptance, so the sensorial characteristics of edible insects and foods which incorporate insects as ingredients, for example insect flour, are pivotal for minimizing rejection and making them more attractive to consumers (Cheung and Moraes 2016; Mishyna et al. 2020).

Meyer-Rochow and Hakko (2018) reported that, despite the well-documented aversion that people from western societies have towards insects as food, when insects are turned into flour or paste they are more easily accepted by western consumers because they do realize their presence, as compared with products that are advertised as having insects in their constitution.

A research undertaken with Brazilian consumers indicated that the main reason explaining why the participants do not attribute the food status to insects is the difficulty in perceiving and characterizing them as food, associating them with expression like "no food" or "disgusting." Therefore, production and commercialization of insects as sources of proteins for humans must focus on the barriers of the consumers, by making them believe that it is a good food and linked with pleasant sensations and thoughts. Only then, aspects such as nutritional value, sustainable production, or reduced water footprint will also be included in the decision-making process (Cheung and Moraes 2016). Another study about how Brazilian consumers perceive edible insects showed that men are more prone to consume insects than women. Although it was observed a general preference to consume "disguised" insects, in the form of flour, for example, there were some participants who prefer the whole insect, especially those more familiar with this type of consumption (Schardong et al. 2019).

A study was undertaken with German consumers to examine the factors determining acceptability of edible insects (whole or processed into insect-based foods) (Orsi et al. 2019). The researchers found that there is a low disposition among Germans to try insects, mostly because of psychological and personality barriers including disgust and food neophobia. However, the attitudes were not so strong towards processed insect products, therefore constituting a possible strategy to gradually introduce entomophagy (Orsi et al. 2019).

In the Netherlands, the most important motivations to try eating insect foods are highly variable according to price, taste, availability, and “fit,” which are also factors affecting everyday consumption of commonly consumed more traditional foods. Higher acceptance of insects as food and their related products is more likely for consumers who are categorized as adopters of other novel foods, and which, by this reason, should receive greater attention (House 2016).

A consumer survey was undertaken in some European countries (Germany and Czech Republic in central Europe and Finland and Sweden in northern Europe) to investigate how consumer knowledge affects disposition to buy insect food. The main findings of the study highlighted that the level of knowledge is a determinant of the willingness to purchase insect food; the effects of knowledge were variable according to country or region, differing between countries in central Europe and countries in the northern Europe. Finally, it was also evidenced that the possible marketing of insect foods might be more successful in northern European countries (Piha et al. 2018).

Ghosh et al. (2020) studied the perceptions of Korean and Ethiopian consumers about entomophagy and found that the predisposition of Koreans to eat insect-based foods was substantially higher than that of Ethiopians. Moreover, genders differences were observed, so that male participants on the survey were more prone to eat insects than women. In addition, the results indicated that there is a wrong idea that people from developed countries are not so open to the idea of eating insect as people from developing countries.

Oliveira et al. (2017) produced a flour from cinereous cockroaches (*Nauphoeta cinerea*) which they added into white bread as a way to enrich the product in protein. The inclusion of 10% cockroaches’ flour led to an expressive increase in protein content, by 133%, while at the same time reducing fat content by 65%. The researchers measured the consumer’s acceptance index and obtained a value over 75% in all sensory attributes evaluated. As for the buying intention, 22% stated they would certainly purchase and 41% stated they would possibly purchase the bread with cockroaches’ flour.

In a work by Megido et al. (2016), four different hamburgers were prepared: beef and lentil burgers, and their counterpart versions with 50% insect (mealworm). They observed that testing by means of hedonic assessments reduced insect neophobia. In addition, the participants rated the attributes of taste and appearance with higher scores for the insect-added burgers when compared with the control. Finally, the insect-based burgers were rated between the 100% meat burger and the 100% vegetable burger.

Recent studies have demonstrated that there is a greater disposition, especially among populations not traditionally entomophagous, to consume products which incorporate grounded instead of whole insects. A work by Cicatiello et al. (2020) investigated the determinants for acceptance of insect-based snacks among Italians, namely products with whole insects versus products that included insect flour as the principal ingredient. Despite the still existing strong cultural barriers, there seems to be a willingness to test some insect-based products among young Italian consumers, because towards those products they do not feel the same level of repulse as for the products where the whole insect is fully visible.

A relevant number of works continue to focus on the use of insects as food or food ingredients for human consumption, either from the point of view of the products’ characteristics or the consumer acceptance. Food neophobia determines to a great extent the consumer’s decision making when they have to opt between unknown new foods or those that he already fully recognizes. However, there are also neophilic consumers, who are willing to try new foods and can develop a good acceptability towards the taste of new foods. It has been reported that the liking for new foods raises as consumers are increasingly exposed to them, and therefore become more familiar with their characteristics (Loss et al. 2017; Guiné et al. 2020a,b).

6.3 New gastronomic trends

Preparation and enjoyment of foods are seen as multi- and transdisciplinary phenomena. From the primary production of animal and agricultural products, until they can be regarded as food, they encompass many operations, including processing, cooking, and the ultimate experience of eating and sensing the product (Fooladi et al. 2019).

According to Traynor et al. (2020), culinary education has an important impact on the attitudes and behaviours towards novel food products, so that individuals with culinary education tend to have a greater overall liking for innovative products.

The perception of insects as food has been gradually establishing in places where they were not traditionally seen as food. Insects have been introduced into high-profile spots, such as culinary events, gastronomic shows, and chef's recommendations. According to Chef Hal Daniel, an entomophagy expert and Biology Professor at East Carolina University, insects are the green food of the future. There is a recognized role of chefs in introducing insects into gastronomy in the western countries, by making them more popular and seen as trendy and exquisite (Cheung and Moraes 2016; Mishyna et al. 2020).

However, the willingness to try new and unfamiliar food has been shown to be guided both by beliefs regarding a food's disgusting properties and by interest, where interest in trying new things has been defined as an important motivational aspect in food choice (Martins and Pliner 2005; Sogari et al. 2017). This also indicates that there is great value in increasing our understanding of the factors that make us interested and choose certain foods (Mancini et al. 2019).

7 Conclusions

Insects have demonstrated a high potential for the future of the mankind, from many perspectives: food security, sustainability and environmental concerns, or socio-economic relevance. Regarding the environmental pressures, insects can be produced in much smaller space, using less water (only 3% of that used for beef production) and less feed (only 8% of that used for beef production). Considering the social point of view, insects provide income to small family farms as well as to many intervenient along the food supply chain, with important social benefits particularly for typical low income countries.

The use of edible insects spans different applications, from animal feed to processing of insect-based foods and gastronomic use. The domain of animal feed is unquestionably a growing market all over the world. Insects are part of daily diets for many people in the planet, but some resistance still persists in other regions of the globe, while also some consumers are avid to try new products and experiences allied to the use of non-conventional foods. Although the role of consumer is unquestionably important, other aspects are also relevant, because the production, commercialization, and utilization of edible insects as food for humans and feed for animals encompass a varied range of regulations, which need to guarantee aspects such as the quality of the products and their safety to protect the consumer.

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