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Insects as food and feed, a new emerging agricultural sector: a review

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REVIEW ARTICLE

Abstract

During the last five years the scientific knowledge on insects as food and feed has been growing exponentially. At the same time, the industrial sector is increasingly engaged in rearing, processing and marketing of edible insects. Considerable attention is given to the black soldier fly as it can convert organic waste streams and transform it into several feed, food and industrial products. The farming of insects has an environmental impact which is lower than that of livestock species. The profitability of industrial production of insects as feed depends very much on the availability and applicability of cheap non-utilised side-streams. Microbial communities and their relationship with insects deserve full attention as it may help in the conversion of organic side streams of low economic value. Nutrition and health benefits for animals and humans need further exploration, also considering that insects have the largest anti-microbial peptide reservoir of all animals. Plant health can also be promoted by using chitin-containing leftover substrates as fertiliser. As insects have only recently been considered as food or feed, legislation trails developments. Therefore, politicians need to be assured that rearing and processing techniques are such that insect products are guaranteed free of chemical and microbial contaminants. Consumers are becoming more and more aware that insects as food are a viable option. Insects need to be processed into ingredients, that can be applied for safe and appetising products. The insect sector is maturing fast, but still faces many challenges, which can only be met when all stakeholders closely cooperate.

Keywords: edible insects, insects as food and feed, black soldier fly, nutrition, health, environment, industrial production, food safety, consumer attitudes, processing

1. Introduction

Insects as food and feed are receiving much attention lately. This is exemplified by the increasing numbers of scientific publications and private enterprises engaged in producing insect products. This review is intended to cover recent developments in this field and to indicate how these contribute to a new emerging sector of insects as food and feed.

It is very likely that early humans already ate insects (Van Huis, 2017). The general notion that edible insects are either a fall-back food or a food used only in marginal environments has been questioned (Lesnik, 2017). Recent evidence suggest that 1.8 million years ago insects in Tanzania were a major food source (Heriot-Watt University, 2018). Primates used the enzyme acidic mammalian chitinase to digest the chitin in insect exoskeletons, which have long been considered indigestible (Janiak *et al.*, 2018). There is a general gradient pattern in reduction of edible insects with increased latitude (Lesnik, 2017), probably because in tropical regions insects are more abundant and easy to harvest (Van Huis, 2018).

The practise of eating insects in different parts of the world has been extensively reviewed (Bergier, 1941; Bodenheimer, 1951; DeFoliart, 2002). It has been termed entomophagy by western people, denoting a peculiar habit of eating a strange food (Evans *et al.*, 2015). Gradually interest in the western world started to emerge of insects as food (Durst *et al.*, 2010; Le Gall and Motte-Florac, 2016; Motte-Florac and Thomas, 2003; Paoletti, 2005), but often the focus was on the consumption of insects by people in the tropics. Also the many publications on edible insects by Julietta

Ramos Elorduy (Pino Moreno, 2016) in Mexico and the one by Malaisse (1997) in central Africa, served that purpose. The publication by FAO and Wageningen University & Research (Van Huis *et al.*, 2013) indicated that insects are a viable food and feed option, not only for people in the tropics but also for people elsewhere (Vantomme, 2017). This prompted the recent publications on exploiting insects as food and feed globally (Dossey *et al.*, 2016; Halloran *et al.*, 2018a; Van Huis and Tomberlin, 2017b). National and international conferences on the topic are now being organised.

The question one may ask is why this food source was ignored for so long outside the tropics. Several reasons have been put forward: (1) low availability of small insects (only a part of the year) in temperate zones (Van Huis, 2017); (2) in agriculture insects are considered pests (Van Huis *et al.*, 2013; p. 39); and (3) low esteem for insects, cultural conditioning and prejudice (Bequaert, 1921; DeFoliart, 1999; Looy *et al.*, 2014). It is often not realised that the ecological services of insects are immense. Noriega *et al.* (2018) classified the services as provisioning (e.g. medicine, nutrition, industrial), regulating (e.g. biological control, pollination), supporting (e.g. decomposition, dung removal, recycling, seed dispersal), and cultural (e.g. bio-indicators, recreation, religion and spiritual values). Let us just mention the value of pollination (235-577 billion US$ annually) (IPBES, 2016) and natural biological control (thousands of natural enemies keeping potential pests at non-damaging levels at an estimated value of 400 billion US$ per year (Van Lenteren, 2006). We will concentrate on the supporting services (nutrition) and then only as food for humans or pets, either by consuming insects directly or through production animals (fish, poultry or pigs).

2. Interest growing rapidly

The academic interest of using insects as food or feed is exponentially increasing. I searched in the Web of Science for 'edible insects', 'black soldier fly' (or its Latin name *Hermetia illucens*) as an example of 'insects as feed', and 'mealworm' (and 'edible') as an example of 'insects as food' and found the largest increase occurring after 2015 (Figure 1).

More than 2000 species are consumed by humans (Jongema, 2017), mainly in tropical countries. If we consider which insect species are reared in the western world for food, it turns out these are species that were reared already in order to feed house pets, including reptiles and amphibians. These insects involved are: (1) mealworms – yellow mealworm (*Tenebrio molitor*), the lesser mealworm (*Alphitobius diaperinus*), the superworm (*Zophobas morio*); (2) crickets, mainly the house cricket (*Acheta domesticus*), but also the tropical house cricket or banded cricket (*Gryllodes sigillatus*) and the two-spotted cricket (or African or Mediterranean field cricket) (*Gryllus bimaculatus*); (3) several locust species such as the migratory locust (*Locusta migratoria*) and the desert Locust (*Schistocerca gregaria*); and (4) others as by-products from the silk industry (pupae of the domesticated silk worm *Bombyx mori*) or from beekeeping (the drones) (Ambühl, 2017). If we consider insect species as feed we find also mealworms but in addition, the black soldier fly and to a lesser extent the house fly (*Musca domestica*) are targeted. Both can be reared on organic side streams, with the first one on most kinds of substrates.

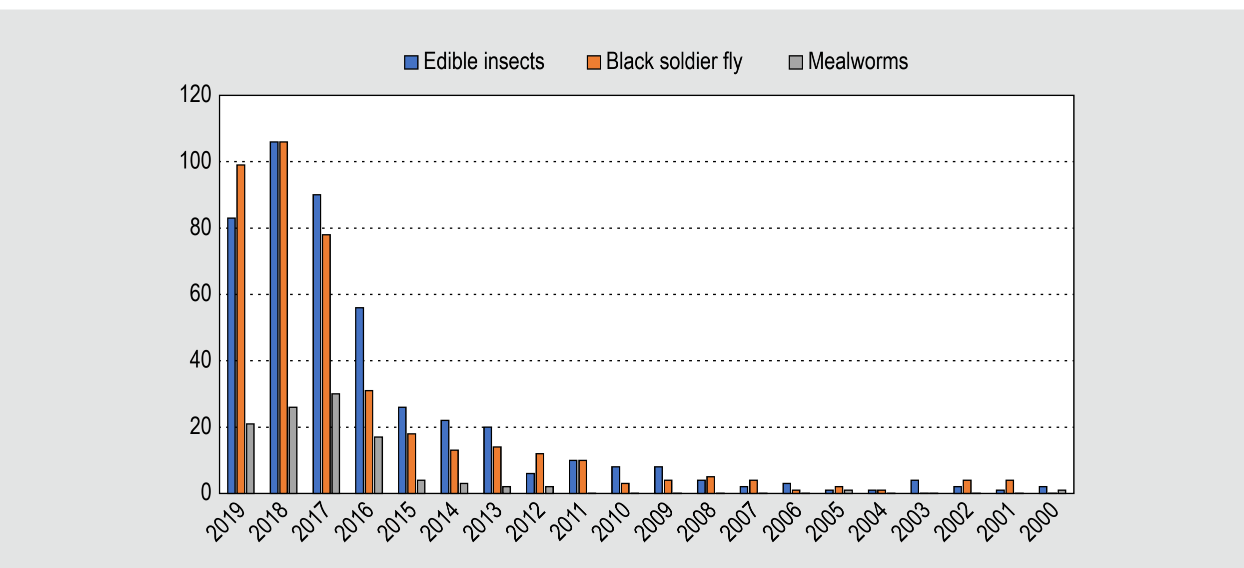

Figure 1. Number of published articles according the Web of Science using 'edible insects', 'black soldier fly' or '*Hermetia illucens*', and 'mealworm' and 'edible' (1 July 2019).

The number of companies in the world working on insects as food and feed, not including insect industry organisations and insect advocacy organisation, is estimated in April 2019 to be more than 250 (BugBurger, 2019). Some of them have received millions of dollars as investment (Feed Navigator: www.feednavigator.com).

3. Black soldier fly

Why is there such a tremendous interest in the black soldier fly the last few years? For example, during the 'Insects to Feed the World' conference May 2018 in Wunan China, 40% of the presentations and posters were about this species. One of the earliest records on *H. illucens* have been in the forensic entomology, an article by Dunn (1916) a hundred years ago on flies found in a human cadaver. One of the first articles on the use of the black soldier fly as feed were for poultry (Hale, 1973) and aquaculture (Bondari and Sheppard, 1981). One of the first articles dealing with the black soldier fly as biowaste converter came a thirteen years later (Sheppard *et al.*, 1994), although their role in reducing manure accumulation (Tingle *et al.*, 1975) and house fly populations in manure (Furman *et al.*, 1959) was already known. Most of these publications came from Georgia, USA. The world distribution of the black soldier fly is given by Rocha Oliveira *et al.* (2015). The species probably originates from the tropics and subtropics of both Americas (very likely South America), and became by man's activities widespread all over the world (excluding colder areas) (Roháček and Hora, 2013).

Tomberlin *et al.* (2015) made an appeal to scientists, policy makers, government officials and food production representatives to create legal opportunities for this promising and sustainable resource to be explored and ultimately implemented. Researchers and entrepreneurs affiliated with universities and industries, respectively, from 18 nations distributed across North and South America, Europe, Asia, Africa and Australia contributed to the development of this article. The recent interest of the black soldier fly is not only academic but also commercial considering the number of companies worldwide that are now producing the insect. There are very large companies supported by large investments. However, there are also smaller ones that often need to organise themselves in cooperatives in order to be able to be competitive with the large ones. What are the benefits of using this insect? One the major advantages is that it can thrive on several organic side streams, including manure and catering waste, although those are not yet allowed to be used in the European Union. This list of organic side streams that can be used is large (Van Huis and Tomberlin, 2017a), and other ones are continuously added (Beskin *et al.*, 2018; Moula *et al.*, 2018; Rehman *et al.*, 2017; Xiao *et al.*, 2018). This of course fits well in the policy of a circular economy now adopted as a sustainable development strategy in European and Chinese policy making (Ranta *et al.*, 2018). Biodegradation can be the purpose, such as in China where manure and catering waste are targeted (Zhang *et al.*, 2020). However, bioconversion or biotransformation are more often envisioned. Producing feed for pets, fish, poultry and pigs is then intended. In the European Union (IPIFF, 2019), black soldier fly larvae and prepupae when reared on materials of vegetal origin are allowed as pet food and since mid-2017 also as fish feed. It is expected that in the next few years it will be allowed for use in pig or poultry feed. Insect-derived fats are allowed as well as live insects. Legislation must be adapted as the original prohibition was the consequence of the mad cow disease in which it was stipulated that animal by-products (insects and their derived products but excluding live insects) are not allowed to be fed to farmed animals. However, likely nobody realised at that time that insects, being animals, could be used as feed. However, it should be realised that when organic waste streams are used as feed, they may contain contaminants, such as bacteria, mycotoxins, heavy metals as well as pesticide residues (Pinotti *et al.*, 2019).

Research is conducted on the microbial community of the black soldier fly not only for optimising the industrial rearing, but also whether it may yield anti-microbials in feed, that can be used in pharma (De Smet *et al.*, 2018). Health benefits of using the black soldier fly have been shown for pigs (e.g. antibacterial effects in prepupal fat against D-streptococci) (Spranghers *et al.*, 2018) and fish (e.g. elevated bacterial diversity and abundance of lactic acid bacteria, which is a potential indicator of improved gut health of rainbow trout) (Huyben *et al.*, 2018).

Left-over substrate can be used as fertiliser (Putra *et al.*, 2017; Rosmiati *et al.*, 2017; Xiao *et al.*, 2018). Chitosan, a derivate of chitin, triggers plant growth and induces plant defence (Sharp, 2013), e.g. providing antifungal and nematocidal activity in fruits and vegetables (Sharif *et al.*, 2018). Wang and Shelomi (2017) discuss their potential use in human foods by processing milled larvae into textured protein. Technological applications are also possible. Protein fractions can be used as raw material for bioplastics (Leni *et al.*, 2017) and protein-based materials, while lipids can be used as bio-lubricants and biofuel (Alipour *et al.*, 2019). From a commercial point of view this is interesting. First because polluted larvae can be used and second because the conversion to high value protein material may be economically more interesting than producing animal feed. Chitin and its derivate chitosan can be used to produce nanofibers (Zimri, 2018).

4. Environment

According to Springmann *et al.* (2018) the global food system is a major driver of environmental burdens; between 2010 and 2050 this could increase by 50-90% in the absence of technological changes and mitigation measures. For example, the indicate that it is possible to reduce greenhouse gas emissions from 187 to 90% by using a flexitarian diet. Livestock production is considered among the most ecologically harmful of all anthropogenic activities with massive direct and indirect contributions to global warming (72-78% of total agricultural emissions). This is due to low feed-conversion efficiencies, enteric fermentation in ruminants, and manure-related emissions (Gerber *et al.*, 2013). This causes widespread eco-degradation in terms of land degradation, loss of biodiversity, global warming and stress on water and soil resources (Tabassum *et al.*, 2016). That is why a lot of attention is now paid to alternative food proteins such as plant proteins, cultured meat, insects, and micro-algae and macro-algae (Loveday, 2019). This review deals only with insects.

The environmental effects of insects as food and feed have recently been reviewed with reference to insects collected from nature and when reared (Van Huis and Oonincx, 2017). This review focuses on insects when reared.

A life cycle assessment is a widely accepted method to quantify greenhouse gas (GHG) emissions, and other environmental parameters, such as land or fossil energy use. Parameters are then quantified along the entire life cycle of a product. This is called an attributional life cycle analysis. Using such a life cycle analysis approach, mealworm had lower greenhouse gas emissions, and used less land and water than common production animals (Miglietta *et al.*, 2015; Oonincx and de Boer, 2012). However, benefits can be lower than expected when alternative uses of organic side streams are taken into account, which has been termed 'consequential life cycle analysis' (Van Zanten *et al.*, 2018). Thévenot *et al.* (2018) concluded that the environmental impact (energy, CO_2-eq climate change, acidification potential, eutrophication potential and land use) of producing mealworms needs to be lower in order to perform better than with soybean or fishmeal. Tallentire *et al.* (2018) looked at the environmental burdens of alternative proteins in the total feed required by a chicken. Mealworms scored better than soybean for greenhouse gas emissions, phosphorus excretion and land use, but not for nitrogen excretion.

Perednia *et al.* (2017) compared the production of carbon-based greenhouse gases (direct emissions) from food waste by using either black soldier fly larvae or aerobic microbial decomposition. The larvae were able to consume it in seven days, while decomposition required 45 days. In the first case 29% of the carbon initially present within the system was lost to the atmosphere in the form of CO_2, compared to 49% in the second case. In this case the black soldier fly larvae converted 41% of the feed carbon into body mass in the forms of protein, edible oil, and chitin.

The necessity for innovations to lower environmental impacts for insect products was mentioned by several authors (Berggren *et al.*, 2019; Halloran *et al.*, 2018b). To reduce environmental impact, upscaling and the use of alternative energy sources for processing was mentioned by Smetana *et al.* (2019), but for them the most crucial factor was considered to be the availability of non-utilised (not for animal feed) side-streams.

Besides, it is possible to use organic side streams as feed for the insects. Bosch *et al.* (2019) reviewed forty articles dealing with environmental impact (global warming potential, energy use, and land use) of manure, catering waste or municipal waste conversion by black soldier fly larvae. The impact was lower than that of fishmeal and soy, but not when larvae converted substrates which contained food and feed products such as sorghum and DDGS (dried distillers' grains with solubles).

Biowaste treatment can be a solution to waste management while at the same time providing a protein source. Black soldier fly larvae can be used to treat a variety of organic side streams including municipal waste (Lalander *et al.*, 2019; Sarpong *et al.*, 2018). In Indonesia, the black soldier fly was used for biowaste treatment which resulted in low direct GHG emissions compared to composting, while global warming potential was reduced (Mertenat *et al.*, 2019). The black soldier fly is also able to degrade residual antibiotics, such as tetracycline in manure, which poses risks to ecosystems and public health (Cai *et al.*, 2018) and pesticides (Lalander *et al.*, 2016).

In a review on alternative feed ingredients for livestock, Pinotti *et al.* (2019) concluded that insects have excellent potential. This mainly because of insects' capability to upgrade food waste biomass. The type of waste material does not seem to influence the protein content and has only an effect on the fat and ash concentration. According to the authors, insects products can meet high quality and safety standards when produced in line with the criteria set by major feed/food authorities.

However, the production of the insect products needs to be more efficient. Although trading prices of insect products have come down, the lesser mealworm is still six times and the black soldier fly nine times more expensive per unit of protein then soymeal (Pinotti *et al.*, 2019).

Styrofoam, expanded polystyrene foam, such as disposable cups and boxes, or cushioning material in packaging, have been proposed for degradation by the yellow mealworm. However, although the foam feeds can maintain the insect's life and produce eggs, it was not economically feasible (Nukmal *et al.*, 2018). *Tenebrio obscurus* has also been proposed as a likely candidate to be able to degrade plastics (Peng *et al.,* 2019).

5. Industrial production

One of the major problems with insect production is the high production costs as they must compete with the common feed (soy and fishmeal) and food products (ABN AMRO/BOM, 2016). This has to do with the labour costs involved and many companies are engaged in automation processes (Meuwissen, 2011). Patents have been filed on different aspects of the automation processes. Examples or patents filed in 2018 are: the light regime, separating insects from the substrate, water delivery systems and processing (US patent applications: 0065152, 0220632, 0271056, 0360008, respectively). However, the technologies developed after a lot of trial and error are often very simple and easy to copy, which is why companies are very secretive about their production processes. Another significant cost factor is the substrate.

Organic side streams of low economic value can be fed to insects but when crickets were fed on a diet largely consisting of straw, they hardly survived (Lundy and Parrella, 2015). However, the black soldier fly was able to digest rice straw (Manurung *et al.*, 2016). Conversion could be enhanced by using bacteria (Rehman *et al.*, 2019) as was demonstrated by Gao *et al.* (2019a) with fermented maize straw. Diverting food scraps from landfills to feed animals is recommended but often restricted by laws and regulations (Leib *et al.*, 2016).

When insects are used as feed, two conversion cycles are needed: from organic products to insects and then from insects (as feed) to production animals. With the interest in the circular economy worldwide, the upcycling of low-opportunity-cost feed (food waste, food processing by-products, grass resources) is being investigated in order to make them more fit as feed directly for production animals (Van Hal *et al.*, 2019), among others by enzymatical digestion processes (Jinno *et al.*, 2018). According to the author, this will make processing of organic waste streams more expensive and therefore economically more challenging to valorise use of insects.

A major question for insect producers is what kinds of waste streams can be used which are not currently utilised for livestock production. Negative value waste streams exist such as manure, and urban and catering waste, but the insect product is then often legally not allowed to be used as feed. Maybe the pros and cons of this policy need further evaluation (Van Huis, 2019). Also the larvae may not perform well, for example because of long development times when reared on manure (Oonincx *et al.*, 2015) or high mortality when reared on straw (Lundy and Parella, 2015). What about when high quality feed stuff would be used for the first larval stages as very little is needed at this early phase of exponential growth and subsequently feed them on low-quality waste streams afterwards? However, changing substrates may not work as black soldier fly larvae have a close association with microbes (Klammsteiner *et al.*, 2018; Wynants *et al.*, 2019a). They probably change the microbial community depending on the nutrient source (Bruno *et al.*, 2019; Jeon *et al.*, 2011) and with that the chemical composition of the substrate (Myers *et al.*, 2008). An innovative solution could be to convert lignocellulose-rich organic wastes (such as dairy and chicken manure) by using lignocellulotic exogenous bacteria (Rehman *et al.*, 2019). These authors assume that the structural and chemical modification of the fibres are beneficial to the associated gut bacteria; it promoted larval growth and the reduction of waste. Co-digestion of black soldier fly with microorganisms has also been done with *Bacillus subtilis* on chicken manure (Xiao *et al.*, 2018) and *Lactobacillus buchneri* on soybean curd residue (Somroo *et al.*, 2019).

Another possibility is to use different insect species for biodegradation, e.g. corn stover can be degraded first by yellow mealworm larvae followed by the black soldier fly larvae, using the residues produced during the first stage (Wang *et al.*, 2017). Maybe it is also possible to mix low-quality waste streams with high-quality ones. Methods should be environmentally and economically competitive to other uses of waste streams such as the conversion into bioenergy and bio-based products (Gontard *et al.*, 2018). For example, food waste can also be converted to, e.g. phytochemicals, bioactive compounds, food supplements, dietary fibres, bio-pigments and colorants, emulsifiers, edible and essential oils, bio-preservatives, biofertilisers, biofuels, and single cell proteins (Gunjal, 2019; Tamer and Çopur, 2014).

Concerning the insects, probably a lot can be achieved with genetic improvement, considering that insects as mini-livestock is new while in common production animals breeding has been going on for more than 70 years (Harris and Newman, 1994). Insects have a short life cycle, from about 10 days for the house fly to two months for mealworms, while for common production animals it is from six months for chickens to two years for cows. This means that there are better opportunities to genetically improve insects than common production animals. Eight years selection in yellow mealworm led to increases of pupal size, growth rate, fecundity and feed conversion rates compared to the ancestral stain, although survival was lower (Morales-Ramos *et al.*, 2019). Also, it may be possible to select lines of black soldier fly which could handle certain types of organic side-streams (Fowles and Nansen, 2019).

6. Nutrition, health and acceptability

The possible health effects of insects as food for humans or feed for animals besides there nutritional value, have been summarised by Roos and Huis (2017) and Gasco *et al.* (2018), respectively.

Humans

The consumption of insects in the western world often is often limited to the occasional snack (House, 2019). However, what if they could be added to staple foods to reach a larger proportion of the population? At the same time, it could add more essential amino acids to the diet and protein-enrichment of staple foods is considered a challenge for the food industry. When mealworms were added to bread (5 and 10% substitution of wheat), technological features were not affected, and the protein content was enriched (Roncolini *et al.*, 2019). Of course, this would only be environmentally beneficial if people for this reason would consume less meat. With this experiment the feasibility to scale up to industrial level was demonstrated, although safety issues need further consideration.

As a general strategy it is has been tried to increase the acceptability of insects by incorporating them in common food items, e.g. mealworm larvae and silkworm pupae (Kim *et al.*, 2016) or crickets (Keto *et al.*, 2018) in sausages, crickets in energy, protein bars and pork pâté (Adámek *et al.*, 2018; Smarzyński *et al.*, 2019), and termites (Kinyuru *et al.*, 2009) and crickets (Alemu *et al.*, 2016, 2017; Pambo, 2018; Pambo *et al.*, 2018) in buns, and pastas (Enwemiwe and Popoola, 2018; Lombardi *et al.*, 2018).

Insects are also used in food fortification programmes by adding them for improvement of micronutrient nutrition. It is often a health policy to reduce the number of people with dietary deficiencies within a population. For example, in order to treat and prevent malnutrition in infants and children, fortified blended food products have been proposed by addition of products containing arthropods (Michaelsen *et al.*, 2009): spiders in Cambodia (Skau *et al.*, 2015), caterpillars in the Democratic Republic of Congo (Bauserman *et al.*, 2015a,b), and crickets (Homann *et al.*, 2017) and termites (Konyole *et al.*, 2012) in Kenya. This is often to combat iron deficiency anaemia which affects more than a quarter of the children (Lopez *et al.*, 2016). Many insect species have shown not only to have a high concentration of iron but also of zinc (Mwangi *et al.*, 2018).

An interesting development is to change rearing condition such that it increases the nutritional quality of the insects, e.g. by adding linseed (a source of n-3 fatty acids) to the diet (Oonincx *et al.*, in press) or by exposing the insects to ultraviolet radiation (synthesis of vitamin D) (Oonincx *et al.*, 2018). Dietary proteins and protein-derived peptides may improve human health, e.g. peptides derived from lesser mealworm larvae can inhibit enzymes, that play a role in glucose metabolism, and thus in the management of type 2 diabetes (Lacroix *et al.*, 2019). There may also be positive effects of insect consumption on the microbiota of the human gut as was shown by Stull *et al.* (2018) for the banded cricket.

Animals

When broiler chicks were administered yellow mealworm and super mealworm larvae as alternatives to antibiotics in broiler chicks, cecal *Escherichia coli* and *Salmonella* contents were reduced, while serum IgG and IgA levels improved (Islam and Yang, 2017). This was attributed to combined effects of the chitin content of insect larvae and probiotics. This may also change the perception of the lesser mealworm as a pest in commercial poultry farms, where it serves as reservoir and vector for many pathogens (Rumbos *et al.*, 2019).

It is known that black soldier fly (Erickson *et al.*, 2004), but also the house fly (Nordentoft *et al.*, 2017) reduces pathogenic bacterial strains in poultry manure. *Salmonella enterica* serovar Gallinarum is a pathogen, causing typhoid fever in chickens. Inclusion of black soldier fly in the feed stimulates the immune response in broiler chickens (Ebertz, 2019). The reason was unknown. However, overall, adding 0.2% chitosan in the diet did already reduce colonisation of *S. enterica* serovar Typhimurium in broiler chicks (Menconi *et al.*, 2013). The use of black soldier fly larvae in reducing pathogens is more sustainable than the use of agents such as antibiotics. However, it is unknown which are the components in the larvae responsible for the observed immune system enhancing effect.

Melanin, a phenol compound, contributes to dark colour of insect cuticle and is another bioactive compound. It is used for treatment and prevention of hepatic diseases, stress, and tumours (Nekrasov *et al.*, 2018). The melanin found in the black soldier fly is eumelanin, likely with a broad range of antibacterial and antifungal activities (Ushakova *et al.*, 2018). The maximum melanin content was detected in the pupae, while the synthesis was most observed at the prepupa stage. In pupae, it is mostly associated with lauric acid with a proportion of 80% in melanin-chitosan complex (Ushakova *et al.*, 2017).

7. Food safety, legislation, insect welfare

Allergy

Patients allergic to crustacean or house dust mite have shown cross-reactivity against the grasshopper *Sphenarium mexicanum*, the desert locust, the field cricket, the house cricket, the yellow mealworm (Pali-Schöll *et al.*, 2019; Sokol *et al.*, 2017; Srinroch *et al.*, 2015; Verhoeckx *et al.*, 2013, 2014). The major cross-reactive proteins are tropomyosin and arginine kinase, well known allergens in arthropods. Food processing can reduce the risk of cross-reactivity and allergenicity of edible insects (Pali-Schöll *et al.*, 2019; Van Broekhoven *et al.*, 2016). To reduce allergenic risk, insect products need to be properly labelled.

Chemical and microbial contaminants

Pathogens

Whether *Salmonella* sp. could be detected in yellow mealworm larvae depended on the level of contamination in the wheat bran (Wynants *et al.*, 2019b). Edible insects may contain antibiotic resistance genes but this is comparable to other food items (Vandeweyer *et al.*, 2019). Feed may contribute to the occurrence of antibiotic resistance genes and/or antibiotic-resistant microorganisms in yellow mealworm larvae (Osimani *et al.*, 2018). This means that regular microbial monitoring on pathogens of substrates and the larvae is required and the survival of the pathogens should be studied after subsequent processing steps.

Mycotoxins

The question is how insects deal with contaminants, such as mycotoxins, when grown on diets composed of organic by-products. When diets were contaminated with the mycotoxin deoxynivalenol, yellow mealworm larvae developed normally and degraded the mycotoxin (Van Broekhoven *et al.*, 2017) to concentrations below regulatory limits for food or feed (Sanabria *et al.*, 2017). What is the potential of mycotoxins to accumulate in larvae of the lesser mealworm and the black soldier fly (Camenzuli *et al.*, 2018)? When feed was spiked with aflatoxin B_1, deoxynivalenol, ochratoxin A or zearalenone, and as a mixture, none of the mycotoxins accumulated in the larvae and were only detected in black soldier fly larvae at very low levels. Both insect species excreted or metabolised the four mycotoxins present in their feed. In another study (Purschke *et al.*, 2017a) also no accumulation of aflatoxins $B_1/B_2/G_2$, deoxynivalenol, ochratoxin A, and zearalenone was found in black soldier fly larvae However, the toxicity of the resulting metabolites needs to be further investigated. Ochoa-Sanabria (2019) proposed to feed mycotoxin-contaminated wheat to yellow mealworm larvae in order to generate a safe protein replacement for animal feed.

Pesticides

The accumulation of insecticides (chlorpyrifos, chlorpyrifos-methyl, pirimiphos-methyl) was studied in black soldier fly larvae when the contaminants were spiked in the feed (Purschke *et al.*, 2017a). Pesticides did neither accumulate in the larvae nor affected larval growth. Lalander *et al.* (2016) also could not find bioaccumulation, when two fungicides (azoxystrobin, propiconazole) were spiked in the substrate.

Heavy metals

Heavy metal contamination in the diet of black soldier fly impaired larval growth and Cd and Pb accumulated in the larval body, indicating a food safety risk (Purschke *et al.*, 2017a). Diener *et al.* (2015) also found Cd accumulation in the larvae of this insect species, while Pb and Zn were less critical. When heavy metals (Ca, Cu, Pb, Zn) were studied in the yellow mealworm and the superworm, Pb was found below detection limits, but the other metals showed high contents with Ca exceeding sanitary limits, making them unsuitable for consumption (Mlček *et al.*, 2017).

Pharmaceuticals

Antibiotics are commonly used in livestock and poultry farming. Richmond *et al.* (2018) detected 60 pharmaceutical compounds in aquatic invertebrates and riparian spiders in six streams near Melbourne, Australia. The fate of three pharmaceuticals (carbamazepine, roxithromycin, trimethoprim) was studied by Lalander *et al.* (2016) using black soldier fly larvae in bio-composting. They observed no bioaccumulation in the larvae. Also, the half-life of these pharmaceuticals but also of two fungicides was shorter in the fly larvae compost than in the control. The antibiotic sulphonamide may occur residually in manure. At low concentration (>1 mg/kg) there was no effect on larval survival, pupation and eclosion of black soldier fly larvae (Gao *et al.*, 2019b). So, using black soldier fly larvae in composting likely impedes the spread of pharmaceuticals and pesticides into the environment.

Legislation

Boyd (2019) draws attention to the fact that the United States Food and Drug Administration (FDA) has devoted significant attention to insects as defects in human food, e.g. FDA (2016), but comparatively little attention to insects as human food. She recommends that the FDA should make this distinction, stressing that insects should be considered food in the United States. To her opinion this will facilitate cultural acceptance of the use of insects as food.

To make the expanding insect industry successful and sustainable the legal context should receive considerable attention by regulators, legislators, and policymakers. It impacts consumer attitudes and consumption behaviours (Wilderspin and Halloran, 2018).

The EU Novel Food legislation allows the legalisation of edible insect consumption in Europe (IPIFF, 2019; Pisanello and Caruso, 2018). Market permission is considered a first step and more guarantees to producers and consumer are called for (Belluco *et al.*, 2017; Lähteenmäki-Uutela and Grmelová, 2016).

As to feed, insect proteins are allowed for use in for pets and fur animals in the EU. The following insects are allowed as aqua feed since the mid-2017: the black soldier fly, the common house fly, the lesser mealworm, the yellow mealworm, the house cricket, the banded cricket and the field cricket (IPIFF, 2019). The European Commission services are currently exploring the possibilities for proposing a new revision of the feed ban rules in order to authorise pig and insect proteins in poultry feed.

What is not allowed in the EU is to use animal manure, catering waste and former foodstuff (meat and fish) as feed. However, more research may be needed to check whether the use of animal manure should be allowed, considering that there is about 1.4 billion tonnes potentially available for processing each year in the EU (Foged *et al.*, 2011). Manure can be used as fertiliser in agriculture, causing environmental problems, such as odours, soil and water contamination and pollution. Moreover, its storage leads to emissions of methane and carbon dioxide. Biogas production is one of the options (Meyer *et al.*, 2018; Scarlat *et al.*, 2018) producing digestate which can also be used as fertiliser. However, in regions with intensive livestock production, the nutrient content of the soil is very high. Then biogas digestate and surplus manure must be either transported to other areas with nutrient demand or stored for long periods. It is worthwhile to investigate the pros and cons of studying the possibilities of biodegradation and biotransformation of manure by insects and the associated food safety and environmental risks and benefits (Van Huis, 2019).

8. Consumer attitudes

Sustainability is becoming an increasingly important consideration for consumers when purchasing food. This is shown by the worldwide increase of the organic market value from 18 billion US$ in 2000 to 97 billion US$ in 2017; the highest market share (almost 13%) in 2017 is in Denmark (Willer *et al.*, 2019). In the EU organic meat in retail sales increased in the EU, e.g. from 2.6 to 5.1% in the UK and from 2.4 to 3.7% in France (EC, 2018). Although in Canada, the US, Japan and especially China, meat consumption per capita is in the increase (EC, 2018), beef and pig meat will decline in 15 European countries with about one kg per person from 2018 to 2030 (EC, 2018). For example in the Netherlands, it is already declining: per capita consumption decreased from 77.8 to 76.6 kg from 2007 to 2017 (Statista, 2019). One of the reasons for the decline is the increasing number of flexitarians, vegetarian and vegans, especially among younger consumers. In France, Germany and the Netherlands, the main reason for not consuming meat substitutes is often the taste of meat, while the main reason for not eating meat is animal welfare (Weinrich, 2018). Americans are more inclined to accept insect food than Indians (Ruby and Rozin, 2019). In this study, the major predictor of potential insect consumption for Americans was disgust, followed by benefits, while for Indians it was benefits, followed by disgust and religion.

Attitudes concerning the eating of insects were studied in Finland among vegans, vegetarians, and omnivores (Elorinne *et al.*, 2019). Non-vegan vegetarians held the most positive attitude toward eating insects, mainly because of sustainability reasons, also an important argument for omnivores. Vegans being most neophobic, considered insect consumption as immoral and irresponsible, but disgust factors did not play a role. However, in Germany more than half of the interviewed vegans and vegetarians tasted insects (Rumpold and Langen, 2019). It remains to be seen whether vegetarians, who ethically object meat-eating, would have moral objections against the consumption of insects (Ruby and Rozin, 2019).

There are many insect products on the market. Lamsal *et al.* (2018) summarised the properties and applications within the context of the food and feed industry. In Belgium energy bars, energy shakes and burgers with insects scored highest, and the preferred place to buy is the supermarket (Van Thielen *et al.*, 2019). Although most people in that country are aware that there are insect-containing food products, only 11% tried them, while 32% that have no experience are willing to try them. Psychological barriers could be reduced for consumers of cricket-flour-containing buns in Kenya by giving them opportunities to taste real products and to provide information (Pambo *et al.*, 2018). The more positive evaluation seems to occur by giving information either pre-tasting (Schouteten *et al.*, 2016) or post-tasting (Suzuki and Park, 2018). The texture and appearance of the insect are perceived as stronger barriers than the taste (Sogari *et al.*, 2018), which is why, as a general product strategy insects are incorporated invisibly into familiar products (Caparros Megido *et al.*, 2016; Wilkinson *et al.*, 2018). Market strategies should be tailored towards the consumer. For example, for insect-based products Onwezen *et al.* (2019) recommend using affective (feel good) communication methods for those consumers that are not actively engaged in healthy or sustainable diets. Youssef *et al.* (2019) proposed even more innovative methods in his article 'How to make sustainable foods (like jelly fish) delicious'; the consumers were given multi-sensorial experiences (using projections and audio means).

9. Processing and conservation

How to recover valuable fractions such as proteins and lipids from edible insects and how can they be applied as feed or food ingredients? This has to do with fractionation and extraction of insect components, the characterisation of the fractions in terms of nutritional and techno-functional properties (capacities such as emulsification, foaming and gelation) and the functionality of insect-derived ingredients (Tzompa Sosa and Fogliano, 2017).

The different steps required for processing are described by Rumpold *et al.* (2017). Decontamination is the first step and this can is mostly done by thermal or radiation processes. The second step is drying which can be done by convection, and by contact or radiation. Comminution (grinding or milling) is the next step. However, to facilitate the grinding process a defatting step may be required. One of the problems experienced during grinding of the larvae is browning, either caused either by enzymatic or non-enzymatic factors. The colouring of the larvae was strongest in black soldier fly followed by the yellow mealworm, and was least in the lesser mealworm (Janssen *et al.*, 2019). It depended on the iron content of the larvae impacting phenol oxidase and polyphenols. Browning can be prevented by lowering pH with sodium bisulphite (Yi *et al.*, 2016) or by blanching (Leni *et al.*, 2019; Mancini *et al.*, 2019).

Defatting, a crucial step, prior to protein extraction can be done by mechanically pressing, and by aqueous and solvent-based methods (Soxhlet and supercritical carbon dioxide) methods. For example, the Soxhlet method recovered close to 100% of the lipids of the yellow mealworm, the lesser mealworm and the house cricket, while with the much cheaper aqueous method, it was 19 to 60% (Tzompa-Sosa *et al.*, 2014). Supercritical CO_2 oil extraction of yellow mealworm larvae achieved a high yield of solvent-free oil and a protein-enriched, solvent-free residue at low extraction temperatures (Purschke *et al.*, 2017b). Using the same method with yellow mealworm larvae and the house cricket followed by separation to fine and coarse fractions by air classification generated three fractions: a lipid fraction of triglyceride oils enriched in essential fatty acids, and fine flavour-intense and coarse chitin-rich powder fractions (Sipponen *et al.*, 2017). Oils from the yellow mealworm oil and the house cricket, obtained by aqueous extraction, all had characteristics desirable for table oils and for oils used as food ingredients (Tzompa-Sosa *et al.*, 2019).

For the extraction of proteins, a number of technologies are available such as electrostatic separation, subcritical water extraction, reverse micelles extraction, aqueous two-phase systems, extraction, enzyme-, microwave-, ultrasound-, pulsed electric energy- and high pressure-assisted extraction (Pojić *et al.*, 2018).

The most challenging part is to separate protein from chitin. Chitin can be extracted chemically or biologically via fermentation with microorganisms and enzymes, the latter method being much more environmental friendly (Rumpold *et al.*, 2017). The first method using acid and alkali solutions yielded 4.9% chitin and 3.7% chitosan from yellow mealworm larvae (Song *et al.*, 2018). The enzymatic method was explored with black soldier fly prepupae (Caligiani *et al.*, 2018). With *Bacillus licheniformis* protease a nitrogen solubility of about 60% was obtained. However, the chitin fraction still had a significant residual protein content.

A possibility to obtain innovative healthy foods enriched with insects could be three-dimensional printing of cereal-based products due to their high content of protein (Caporizzi *et al.*, 2019). Because of the scepticism with respect to eating insects in western countries, it could be useful to improve shape, taste and, in turn, their acceptability.

Cultured meat, *in-vitro* cultivation of animal cells, is being researched for the last 20 years as a sustainable alternative to the common meat production using slaughtered animals (Stephens *et al.*, 2019). For the first time it has now been proposed to use insect cell cultures instead of mammalian or avian cell cultures as they seem to require fewer resources and are more resilient to changes in environmental conditions (Rubio *et al.*, 2019).

During processing and storage food safety needs to be assured. When studying microbial dynamics during rearing, processing, and storage of the cricket *G. sigillatus*, feed appeared to be an important source for the cricket microbiota. (Vandeweyer *et al.*, 2018). A post-harvest heat treatment reduced high microbial numbers, while a heat treatment during processing will likely eliminate endospores. A shelf life of six months was considered safe.

10. Conclusions

A new sector of insects as food and feed is emerging. The number of academic publications is growing exponentially. More and more start-ups are engaging in the industry. Some of them are attracting large sums of money, which shows that investors are becoming aware of the business opportunities. Those investments are necessary as a new emerging industry can only thrive by innovations. Production processes must be invented, often from scratch. In order to be competitive, the cost price needs to come down. That has to do with efficiency of production, not only in terms of techniques and methods used in this rapidly evolving industry, but also with the organisms used and the substrate for the insects.

The technology needed to efficiently farm insects is still in a starting phase. What are the challenges and precautions that need to be considered when breeding and maintaining high-quality insect populations for food and feed? This involves techniques typically used in domestic animal breeding programs including maintaining genetically healthy populations by allowing large population sizes, artificially selecting animals for breeding that possess valuable production traits, and allowing natural selection to operate and thereby maintain high fitness and facilitate adaptation to the production environment (Jensen *et al.*, 2017). However, also deliberate selection procedures could result in lines that can deal with certain types of organic side streams.

The other challenge is to find feed substrates for insects. The organic side streams with a negative value, such as manure, or urban and catering waste, are of interest. There are legal impediments, but it should be investigated to which extent they are justified, i.e. whether chemical and biological contaminants should be considered a real problem for food safety. Also, consideration is to be given to the various purposes for which the products from the insect industry can be used: (1) left-over substrate as fertiliser; (2) the larvae/prepupae as food and feed; (3) edible oils in food and feed applications or oils in cosmetics, bio-lubricants, or biodiesel; (4) proteins in food and feed applications but also the technological applications such as bio-plastics; and (5) the chitin and chitosan in biomaterials and biomedical applications (Elieh-Ali-Komi and Hamblin, 2016; Morganti *et al.*, 2018).

The nutritional benefits of edible insects for both humans and animals need further investigation. Beneficial effects on the immune system and the gut bacteria have been shown. However, we do not know much about the use of the anti-microbial peptides of which insects provides the broadest range. This is of particular importance in view of the increasing occurrence of multidrug resistant pathogens towards conventional antibiotics (Tonk and Vilcinskas, 2017). In the house fly and the black soldier fly the existence of anti-microbial peptides has already been shown (Elhag *et al.*, 2017; Guo *et al.*, 2017). Also, the effects on plant health of using the left-over substrates, containing chitin, as fertiliser need further investigation.

Food safety and legislation requires full attention, as it is logical that in a new emerging industry legislation must catch up with new developments. Therefore, attention to the chemical and biological contaminants must be given. The pros and cons of the insect industry, including insect welfare issues, should be brought to the attention of politicians as has been done in the Netherlands (RDA, 2018).

Regarding consumer attitudes, there was a steep increase in public attention during the last 10 years. In 2007, googling 'edible insects' gave 100 hits for newspapers, magazines, blogs and on television. In 2016, this number had multiplied to 6,070 (Shockley *et al.*, 2017). In a short time, the people have become acquainted with the idea that insects can be eaten. Strategies have been devised in order to convince consumers, as resistance has a lot to do with eating habits, customs and psychology. The biggest challenge is to make people consume insects as staple food rather than as an occasional snack. This entails incorporation in main food items. Processing insects into tasty products is a prerequisite. Price is also an issue. Expenditures can be brought down by automating the production process, identifying and preparing cheap substrates on which the insects are grown, as well as the developing efficient processing technologies.

The sector of insects as food and feed is developing fast. Organisations are being formed to embed the industry in a more conducive environment. The sector can only progress when the insect industry, the academic world, governmental organisations and public society closely cooperate.

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