INSECTS AS ANIMAL FEED

NOVEL INGREDIENTS FOR USE IN PET, AQUACULTURE AND LIVESTOCK DIETS

Edited by

Heidi Hall, Elaine Fitches and Rhonda Smith

CABI

Insects as Animal Feed

Novel Ingredients for Use in Pet, Aquaculture and Livestock Diets

Collectively the editors would like to dedicate this book to their family and friends, as without their encouragement and support this would not have been possible.

To my daughter, Ava Rey Rose Hall who allowed me the freedom to follow my dreams.

H.H.

To all who contributed to the EU-funded PROteINSECT project who inspired so many others to pursue their endeavours in the field of insects for feed.

E.F.

To all the visionaries, scientists, innovators, and entrepreneurs who are working to secure a more sustainable global food system.

R.S.

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Foreword

This book highlights the opportunity for the inclusion of insects into animal feed for livestock, pets, aquaculture and exotics. It also details the challenges which still need to be overcome to enable the global establishment of insect farming as a profitable and sustainable source of feed ingredients.

The aim is to provide information to enable all interested parties to evaluate use of insects as feed ingredients as a revenue stream, as a contributor to global sustainability or as a topic for further academic study or engineering challenge. Researchers, legislators, potential producers and investors, nutritionists, veterinarians as well as environmental and social campaigners will all find material in these pages to inform and interest as well as intrigue them.

Insects are the most diverse group of animals on earth, representing up to 90% of species with more than a million described extant species and an estimated 6–10 million species in total. Approximately 2000 of these have been documented as edible. Entomophagy, the consumption of insects, has been common practice in Africa and Asia for over 2000 years, and insects remain an important and nutritive source of protein, fats, minerals, vitamins and fibre for an estimated 2 billion people. Most insects have been, and continue to be, harvested from the wild and this practice is widespread in the Asia Pacific region, both for subsistence and commercial purposes. A limited number of species have been domesticated for centuries due to their valuable products, such as bees for honey and silkworms for silk. However, over recent decades a number of species, such as mealworms and black soldier flies, have stimulated interest for potential farming as feed for livestock, aquaculture, pets and exotic animals.

This interest has largely been driven by increasing demand for animal feed to meet growing consumer needs for meat, milk and eggs for an ever-growing and more urbanized global population. Global compound feed production in 2019 was over 1.1 billion tonnes (t), of which 465 million t were produced to feed poultry, 261 for pigs, 245 for ruminants and 41 for aquaculture. While thankfully the recent Food and Agriculture Organization of the United Nations (FAO) analysis suggests that a global coronavirus disease 2019 (COVID-19)-induced food crisis is not imminent, there continues to be a growing protein deficit that is threatening the long-term sustainability of global livestock production. Increasing awareness of the negative environmental impacts of key traditional feed materials, coupled with the need to reduce reliance upon imported soya bean meal and fishmeal as the principal sources of feed protein, has fuelled efforts to develop alternative and more sustainable animal feed products. Certain species of insects grow naturally en masse on and in organic wastes of vegetal and animal origin offering huge potential for conversion to high-value protein for novel products for the feed industry. Furthermore, residues remaining from the rearing process have value as novel biofertilizers with the potential to enhance crop and soil health, thus reducing reliance on chemical fertilizers. This approach clearly aligns with the circular economy and need to produce ‘more from less’.

An increasing volume of publications report insects and in particular insect protein to be highly suitable for inclusion in the diets of various fish species, crustaceans (prawns and shrimp), chickens (broilers and layers), turkeys and pigs. Other insect products could also be nutritionally advantageous, not just as a protein source but as alternative sources of energy in the form of insect oil. Insect chitin also shows potential as a promoter of animal gut health and plant immunity.

Insect farming offers the potential to provide locally-sourced high quality feed products, boost economies and reduce importation of conventional feeds. This aligns directly with the European Union’s ‘Green Deal’ which targets reductions in greenhouse gases alongside a drive towards locally produced, homegrown and organic produce. Insect-based proteins have been showcased as one potential solution, but a number of challenges must be overcome for this to be realized.

In the Western world in particular, the economic viability of insect production at commercial scale is a major constraint on current volumes. Other areas of concern are: (i) sourcing of permissible substrates; (ii) consistency of product quality; (iii) product assurance; and (iv) retailer and consumer acceptance. Governmental support to industry is essential to ensuring that insect-derived feed ingredients produced across the world are safe and of consistent quality. To enable full utilization in feed considerable changes are required to legislation concerning insect products. These changes are likely to take considerable time as they must be based on sound scientific evidence to ensure feed safety is not compromised.

If the evidence supports the use of insects in line with circular economy principles, and legislation is introduced to enable this, not only could this innovative feed material become the norm, but also a range of insect-rearing substrates would be considered safe and suitable for use; thus enabling insects to also be utilized as mainstream ‘waste recyclers’, reducing volumes and thus the costs associated with the removal and disposal of such residues.

Insects are adapted to growing on low-value feedstuffs and manures while producing high quality protein and fat in a relatively short period. The potential is evident and significant as long as the inherent risks associated with this novel feed material are mitigated, enabling the industry to leverage both sector and ‘public good’ value in the long term.

For this book, the editors have approached and secured chapters from experts, researchers and business owners from domains across the world where legislation, practice, culture and progress in development and application vary greatly. Through this multi-faceted presentation, the reader will discover not only recent advances in research and practical applications, but also the areas that require further detailed consideration. The range of challenges that still need to be overcome to ensure the safe use of insect products in livestock feeds while also being economically viable and sustainable are considerable.

The editors thank all contributors to the chapters that follow for giving their time and expertise so freely and their patience during the past months.

Heidi Hall, Elaine Fitches and Rhonda Smith
January 2021

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The world map (Fig. A) highlights the global spread of all our authors and contributors.

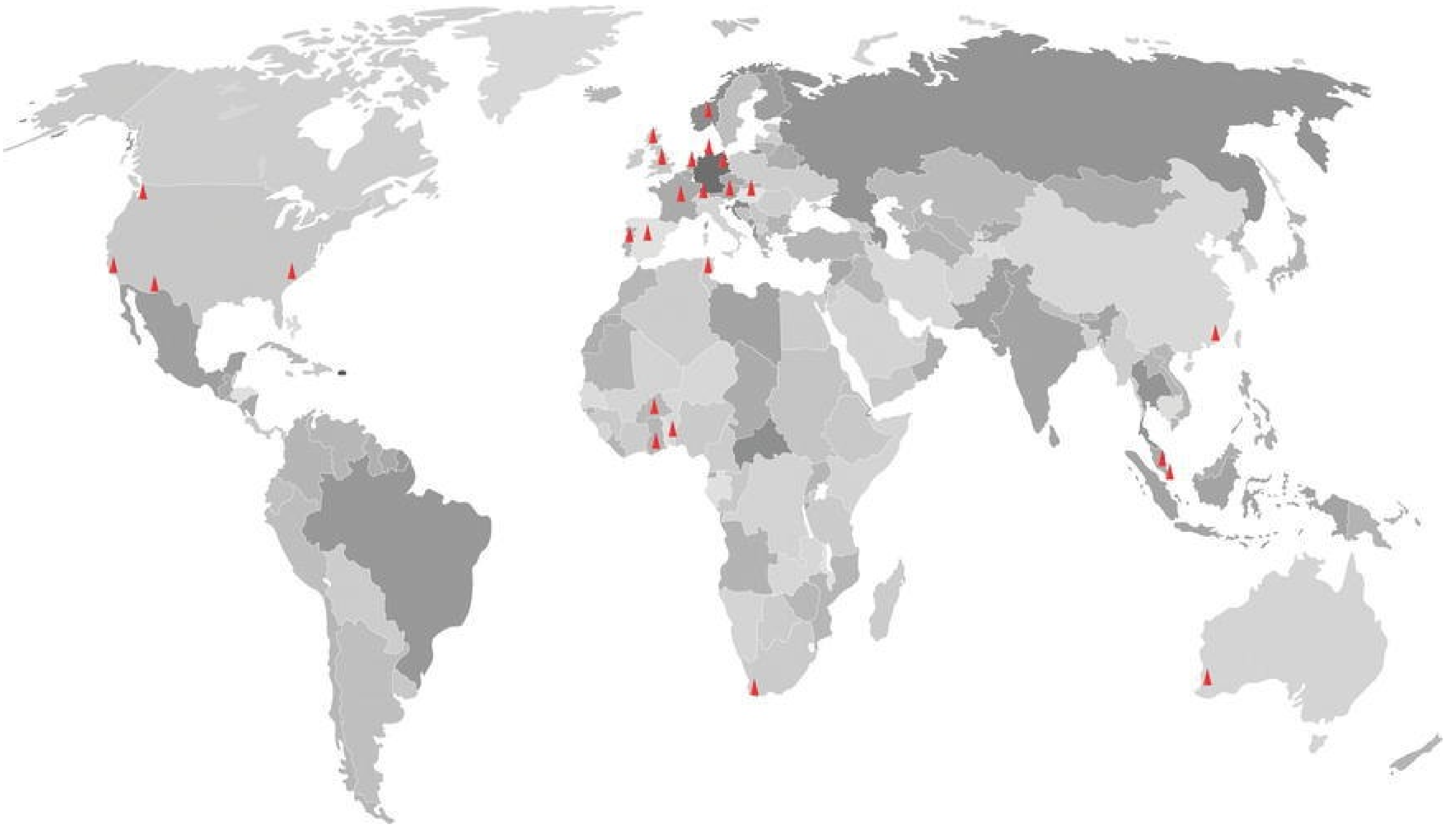

Fig. A. World map showing the global distribution of contributors to this book.

Glossary

Anoxic conditions	An atmosphere lacking free oxygen but may have bound oxygen present
Autotroph	An organism that is able to form nutritional organic substances from simple inorganic substances such as carbon dioxide
Bokashi	A composting process
Dejectate	Insect excreta
Essential amino acids	An amino acid that cannot be synthesized *de novo* by the organism fast enough to supply its demand, and must therefore come from the diet
Exuviae	The cast or sloughed skin of an animal, especially of an insect larva
Feed conversion ratio (FCR)	The feed requirement per unit of body weight gain. It is commonly used as an indicator for feed efficiency
Global warming potential (GWP)	The heat absorbed by any greenhouse gas in the atmosphere, as a multiple of the heat that would be absorbed by the same mass of carbon dioxide
Greenhouse gas (GHG)	A gas that absorbs and emits radiant energy within the thermal infrared range, causing the greenhouse effect
Hazard Analysis and Critical Control Point (HACCP)	A systematic preventive approach to food safety from biological, chemical, physical and (more recently) radiological hazards in production
Hemimetabolous	Larvae hatch into a form similar to the adult
Heterotroph	An organism deriving its nutritional requirements from complex organic substances
Holometabolous	Larval stage is followed by a pupal stage and then the adult form; three distinct phenotypes
Integument	A tough outer protective layer, especially that of an animal or plant
Land use change (LUC)	Conversion of land from its natural state to one which benefits humans
Life cycle assessment (LCA)	Methodology for assessing environmental impacts associated with all the stages of the life cycle of a commercial product, process or service
Metamorphosis	In an insect or amphibian the process of transformation from an immature form to an adult form in two or more distinct stages
Omnivore	An animal or person that eats a variety of food of both plant and animal origin
Oxic conditions	An atmosphere containing free oxygen
Vermicompost	The use of earthworms to convert organic waste into fertilizer

1 The Challenges Facing the Feed Industry

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1.1 Setting the Scene

As an integral part of any food supply chain, the animal feed industry has the potential to be perceived as either part of the problem in the challenge of delivering sustainable food supplies, or the source of meaningful and deliverable solutions. The market served by the feed industry is diverse, including animals grown primarily for meat, dairy and egg production as well as feeds for domestic animals. Today the industry could be described as operating within the context of a perfect storm. The combination of often disparate challenges from consumers, retailers, policy makers and not-for-profit interest groups about what modern food systems should look like if they are to meet the requirements to feed people and contribute to improving human health, as well as reversing the worse impacts of climate change while using less land is unique to our times. Insects represent one of a number of emerging novel ingredients which, while currently in their infancy, may in future help alleviate some of these pressures. However, the following aspects would need to be considered if insects where to become a major ingredient in animal feeds.

Each stakeholder group has a broad range of specific interests that establish their motivations and drive their behaviours, although arguably all sit underneath the perception that a focus on their priority viewpoint is the answer to the long-term availability of safe, affordable and nutritious foodstuffs produced within the constraints of a thriving planet. However, global food supply is unique in its relationship to the social fabric of cultures, to financial security and to a local and wider environmental context. Therefore, the stakes are always high with most significant changes risking substantial unintended consequences or trade-offs both locally and globally.

So, who is going to take a lead and change first? What is the animal feed industry's role and what should be targetted first? These are the challenges.

1.2 The Perfect Storm Affecting the Large-scale UK Animal Feed Industry

There are three key factors creating the perfect storm.

First, the multiplicity of competing requirements from retailers. Driven by the need to earn and retain trust from consumers, they seek to evidence that they are acting responsibly about the issues their target customers care about most. The issues may be animal health and welfare, waste reduction, livestock production systems, carbon emissions, deforestation, or a combination of all of them. However, many customers have limited interest in and understanding of the full details of their topic and any price premium, or even cost recovery for a differentiating attribute, is commercially challenging.

Product innovation is the life blood of today's food retailers and recent trends bring great opportunity for them to introduce new propositions and food ranges. Vegan meals is an example. While vegan meals only represented 3.6% of main meal occasions in 2018 there was a 13% year-on-year increase (Cooke, 2019). More significantly only 14% of vegan meal occasions are documented as eaten by vegans – growth over the previous year was driven exclusively by non-vegans (Cooke, 2019). Additionally, introduction of new ingredients or new food concepts such as soya free, can be highly risky. Claims that a product or ingredient is better for the planet, or for animals, can be complicated given the trade-offs required, plus the availability of relevant data insights. The latter may be important for regulators but is not necessarily considered by customers.

Second, policy makers and regulators are often driven by short-term political realities and the need to retain the base requirement of ensuring that food supply chains operate to deliver affordable and safe food for all. The coronavirus disease 2019 (COVID-19) pandemic has brought this need into sharper focus. However, the requirement to deliver against legally binding net zero climate commitments will require a new food and feed policy framework as the marketplace will not deliver without direct intervention. The UK's exit from the European single market provides the best opportunity in a lifetime for a substantial reconfiguration of rewards, incentives and penalties for protein production to deliver against new political priorities. There will be winners and losers but the specific impacts on protein and milk supply chains are unclear and are unlikely to be fully visible within the next 10-year period.

Third, the increasingly effective and professional engagement and communication techniques being used by not-for-profit interest groups. These groups are able to cost-effectively tap into the interested population groups through the use of increasingly sophisticated digital influencing tools. Such tools help drive changes in purchasing behaviours – sometimes with a strong underlying evidence base but often with selective use of available facts and context. These interest groups are being successful in portraying modern protein livestock and dairy systems as highly damaging not only to the planet but also to animals, while also highlighting and signposting the growing availability of alternative food choices.

These three factors are moving in different directions, creating a maelstrom of change. This is contributing to a sense of real dilemma on what and where the food and feed industries should prioritize change, both in the short and in the medium term, to ensure they thrive in the future. One specific area of both opportunity and challenge is the future design of animal feed formulations which significantly impacts all key aspects of modern feed supply. These factors are ingredient choice, ingredient procurement and product manufacturing.

1.3 Today’s Landscape

In common with many related sectors, the basic components of efficient and productive animal feed suppliers have priorities that evolve and change over time. Today, priorities centre on themes such as achieving the ‘best’ nutrition, safety and regulation, market needs, cost optimization, efficiency of its own operation and the environment. All these elements are being managed on a daily basis and the relative priorities will change according to industry and consumer or retailer demands. The authors’ experience is of the UK feed industry and so the content following will relate directly to that. However, peers in the global sector, or indeed the feed businesses of integrated operations, will touch the same concerns even if the highest priority may be different at any given point in time.

Best nutrition

The focus of the animal feed industry has always been provision of the best nutrition to maintain the health and welfare of the animal, and to deliver the outcome that the downstream customer requires. In the mid- to late twentieth century, there was huge progress made principally in the USA and Europe on the nutrient requirements of livestock delivered by a combination of government and academic facilities. However, by the turn of the century, financial funding from public sources had decreased, hence much of recent research has been achieved by commercial industry, keen to align with genetic progress and continuously seeking the optimum nutrient input to obtain the required livestock output. Research has included: (i) performance and efficiency; (ii) environmental impact of different types and quantities of nutrients; and (iii) health and welfare of livestock and pets. Best nutrition continues to be the priority for the feed industry.

Safety

Safety of products remains a crucial objective of the animal feed industry as a consequence of a number of high-profile feed safety incidents over the last 30 years. The one that caused the greatest global impact was bovine spongiform encephalopathy (BSE) which originated in the UK and affected ruminant animals; it is believed to result in variant Creutzfeldt-Jakob disease (CJD) in humans. Its cause was linked to a deformed protein molecule, a prion, thought to have arisen through the feeding of meat and bone meal as a feed ingredient to ruminants. This put the initial spotlight on animal feed and its safety, reinforced by further feed safety issues, for example dioxins in feed fats and deliberate addition of melamine to feed materials. The animal feed industry has worked hard to improve its reputation in the eyes of the consumer. It cannot afford to be exposed to large-scale feed safety issues in the future.

As a consequence of the feed safety issues in the 1990s, the European Union (EU) published a paper on food safety and took several subsequent legislative actions. This pattern of an immediate legislative response to a feed safety incident is common; hence the global feed industry continually seeks to pre-empt and control such risks.

Increasingly the industry now also needs to consider feed safety risks that have been created intentionally by individuals or groups that have a behavioural or ideological motive for doing so. This might be a disgruntled employee or an external party that has a specific grudge against the factory or business. Equally the industry needs to consider risks driven by economic fraud.

Legislation

Understanding and delivering legislative requirements has become an integral part of the feed industry's daily work. Feed legislation has increased across all countries but there still exists a diversity of standards. Antibiotic growth promoters, for example, were banned nearly 15 years ago in the EU. However, many other countries are only phasing them out in recent years driven by consumer demand, and some are still to do so.

The feed industry has always argued for legislation based on science: for example the establishment of the European Food Safety Authority (EFSA) which provides independent scientific advice. However, recently there are examples where public opinion and influential non-governmental organizations (NGOs) are driving the legislation rather than science, a further challenge for the industry. One consequence is that legislation for the same feed material or product can vary substantially from country to country.

Market needs

Ultimately the feed industry must meet the needs of the market, and these are ultimately driven by the consumer or potentially the retailer's view of the wishes of the consumer. Aversion to the use of legally permitted feed materials such as lard, tallow and plasma (and controlled by the farm assurance scheme) is a reflection of consumer preference, as is the avoidance of the inclusion of legal genetically modified (GM) feed materials in several EU countries.

Environmental impact

Increasingly environmental factors are becoming more prominent within the feed industry. There are three key aspects: (i) the raw materials being used; (ii) the manufacturing process; and (iii) the impact of the feed use.

Deforestation and the impact of land use change (LUC) on greenhouse gas (GHG) emissions is by far the biggest environmental concern today in terms of raw feed material usage – such as palm oil and its derivatives, and soya bean products. While there has been proactive industry activity on limiting deforestation, there are now suggestions of legislative drivers as indicated in the EU Green Deal (European Commission, Secretariat-General, 2019).

There has been a legal requirement to record carbon usage in feed manufacture (Finance Act 2000; UK Government, 2000), hence minimizing energy use by the choice of equipment, the physical nature of the feed and elements of the feed formulation are always key considerations.

The nutrient output, as a consequence of feed design, has increasingly become more relevant over the last two decades. In particular, the need to tightly manage emissions of both nitrogen and phosphorus has been seen in the Netherlands and in the UK. Furthermore, not only the GHG emissions of feed but the product environmental footprint (PEF) of feed products, fundamental to assessing the GHG emissions and PEF of the livestock product, are being reported. There is a growing negative consumer view on the environmental impacts of livestock production which necessitates the collection and communication of accurate and relevant data to evidence responsibility in supply chain management by large-scale food processors.

Cost optimization

The overarching need is to satisfy all the above-mentioned requirements within the feed at the most economical cost. Least-cost feed formulation has drawn negative comment in the past, but ultimately for a sustainable agri-supply industry the aim of each sector must be to meet all product requirements at lowest cost. Certainly, with the often low and volatile level of financial returns in the livestock production and feed industry sector this is essential. Raw materials therefore need to be available in sufficient quantities to justify being used, and the cost per unit of each nutrient versus other materials will ultimately drive their inclusion in the feed formulation or not.

1.4 What Changes Could the Feed Industry Make?

What could be considered as a better outcome for the feed industry while considering the factors examined above? Could we produce a more sustainable feed but what is our definition of sustainability in this context? Could we produce a better ingredient? There are many ways this could be measured.

As feed is the most significant cost in growing livestock it has the potential to dramatically impact the final cost of the consumer food product. It follows that ingredient cost is clearly of indirect importance to the consumer as families are looking for affordable food. However, environmental objectives such as efficiency in land use, both locally and in the regions from which we import our raw materials, are also high on the agenda with an increasing spotlight in the global media. Taking these examples, we can see that consumer concerns and the drivers behind decision making in livestock feed manufacture are often competing. When considering pet food, the feed manufacturer is selling to a customer who is probably making more emotive choices about how or what to feed their animal. Cost is important but the impact of consumer priorities on the environment, for example, may have more of a direct impact on ingredient choices. In other cases customers' decisions are driven by specific need, for example 'raw' and 'meat-only' pet diets have an increased need for resource as they are primarily or wholly meat derived, which means increased use of livestock reared for human consumption being used in pet food. Other diets are in fact 'meat-free' and so pose other challenges for nutritional or welfare reasons.

Feed ingredients and the feed formulation process

One of the most significant changes we could make is to adjust our feed formulation philosophy and process and consider alternative and novel ingredients, including insect products. Insects, such as crickets, mealworms and some species of flies are used for food and feed (van der Spiegel *et al*., 2013). These insects can be farmed and provided as whole or dried insects or larvae, or fractionated into oils, protein meals and high-value components such as chitin (Sogari *et al*., 2019). Advocates of the use of insect products believe they have lower environmental footprint than traditional cereals and legumes such as soya (Oonincx and De Boer, 2012).

To understand the place novel feedstuffs have in feed formulation, we must understand the value of the commonly used feedstuffs. The provision of protein and energy is a fundamental requirement in a diet for any species. For monogastrics particularly, the easiest way to provide these are via imported legumes and locally grown cereals, respectively. According to the United States Department of Agriculture, global production of soya beans in 2019–20 was 340 Mt (USDA, 2020), using 125 Mha of land (FAOSTAT, 2020). This is way ahead of the next most significant oilseed, rapeseed, at 67 Mt. Almost 90% of all soya is crushed to extract the oil and produces the meal as a co-product. The yield of meal from bean is approximately 80% (Medic *et al*., 2014) putting the global output of soya bean meal at around 240 Mt. This meal is almost exclusively fed to livestock species. The reason that so much soya is grown and consumed in animal feed is twofold: (i) the yield of protein is higher than for any other major crop; and (ii) the protein is of high quality, especially for monogastric animals. The two main ingredients of monogastric compound feed are cereals (usually maize or wheat, depending on the region) and protein meals, very often soya bean meal. This is determined by the fact that cereals are relatively low in protein and essential amino acids (e.g. lysine, methionine) and relatively high in energy, whereas soya bean meal is the inverse, except for a relatively low methionine content. This means that it is possible to meet the majority of an animal's requirements for energy and amino acids using these two ingredients. Soya bean contains several notable anti-nutritional factors, such as phytate and trypsin inhibitors, which may cause irritation to the gut, and decrease the quality of the feed. However, these are relatively easily overcome by the use of enzymes (phytase, now ubiquitous in monogastric animal diets) and the thermal and chemical processing used to extract the oil.

For many years, our industry has been assessing alternatives to soya bean meal, primarily to address the environmental concern of soya production and transport. Due to its high nutritional value, availability and low cost, soya bean meal is the benchmark for comparison to new and novel ingredients. Rapeseed, also known as canola, is identified as the next largest oilseed crop by volume. However, some basic analysis of rapeseed meal helps to indicate why alternative ingredients have traditionally failed to match up to soya bean meal. Rapeseed meal is around 10% lower in total protein than soya bean meal (e.g. see Dale, 1996). Furthermore, it is understood to be less well digested (Huang *et al.*, 2006). This means that when it is used in feed formulation it is probably combined with soya bean meal and synthetic amino acids. Other additives may also be needed to enable the formulation to meet the specified nutrient levels. That is not to say that soya bean-only diets do not contain such additives but possibly to a lesser extent. Therefore, formulating with soya bean meal is generally less challenging as it is reasonably well understood.

Other important commonly used ingredients to consider are fishmeal and other non-vegetarian sources of protein. Fishmeal is still used to some extent in poultry and piglet starter diets, despite its high and volatile price. There is a perception that growth performance is improved when it is used and even though the mechanism is unclear it persists in some high-value feed formulations. The aqua nutrition sector is a much more consistent and significant user of fishmeal, certainly, many species of farmed fish are carnivorous and need non-vegetal sources of protein. Likewise, some non-vegetal sources of protein, such as milk-derived ingredients and meat meals, are used in certain geographies for reasons other than just their protein content. Therefore, these ingredients may be difficult to replace with alternatives as they provide further benefit other than cost and availability. As a result, the value of novel ingredients, such as insect meal versus fishmeal and non-vegetal sources of protein, must also be clearly understood to have value in those sectors which use ingredients preferentially over soya.

The future of poultry feed formulation was recently reviewed by Ravindran and Abdollahi (2016). That review focuses on the need to be more precise with our nutrition, gaining new knowledge on nutrient metabolism and requirements and the composition of our feedstuffs. This will undoubtedly apply to all species, not least in fish feed formulation where there is much less available information in nutritional value of ingredients. The authors discuss the poultry industry's current methods of over-formulating when there is doubt in nutrient composition, leading to waste and environmental pollution from excreted nutrients. Precision formulation also allows for decreased costs and fits the model of least-cost formulation and can be a tool to allow better alignment of nutrition to animal needs. This can help to reduce environmental pollution through less waste but requires an increased knowledge of requirements in real time.

Earlier, Leeson (2012) published a view of the future and presented specific challenges to feed formulation that still exist even some time after its publication. For example, Leeson describes growing attention paid to pathogens in feed and that we will increasingly be formulating without various pharmaceuticals including coccidiostats and antibiotics (still relevant in many geographical regions). This will increase the focus on finding other means of supporting good gut health. The fact that birds are reaching target weights at a much earlier age, due to genetic development, is also highlighted. This means that the post-hatch period (say 0–10 days) is a much greater proportion of the bird's life cycle. The digestive tract of the bird is still immature at this stage and it is likely that the digestibility of complex proteins and carbohydrates in cereals and soya bean meal is in some way suboptimal. This may encourage us to look to alternative, more digestible ingredients, and put increased technological focus on our starter diets as opposed to the finisher and withdrawal phases. An interesting perspective from Leeson (2012) is that protein choices may become localized. That is, our global reliance on soya bean meal may be broken down into locally relevant and available alternatives. This may help to meet global demand since there is not a single clear alternative to the total volume of soya bean meal. For example, in the USA, distillers' dried grains (DDGs) have had significant uptake in recent years as bioethanol production has increased and by-products become available. This may also point us to super localized production of novel alternatives such as insects or single cell protein.

Due to changing consumer demands and increased focus on sustainability and environment, we may need to further change the way in which we, as an industry, approach diet formulation. We may want to assign alternative values to our ingredients, aside from traditional nutritional values and cost. In this hypothetical future scenario, we would be redefining least cost as 'least cost for least impact'. There seems to be few peer-reviewed scientific publications on this topic and that is likely because commercial feed businesses are reviewing their own strategies internally. Currently, feed for production species is formulated on the basis of least cost: which ingredients should be included to meet a nutritional and quality specification, for the least possible cost. This is the main driver for soya use; it is low cost, available and enables straightforward feed formulation. Soya is also well understood by nutritionists and formulators.

In the future we may assign characteristics and values such as food miles, environmental score, carbon footprint or similar. This would require detailed information on all ingredients (or at least our major feed constituents). The feed formulator would need complex analysis of the impact of the supply chain of that ingredient but also its impact on the animal being fed. We could envisage a scenario where one particular ingredient has improved environmental metrics but is detrimental to an animal to the extent that undesirable emissions are increased, for example. This highlights a further complexity in the use of future novel ingredients. However, the feed industry may be compelled to move in this direction by the demands of its customers and the consumer, but also by its own ambitions to design and produce more sustainable products.

Another aspect we may consider of alternative and future ingredients is the role that each individual ingredient plays in the diet. Traditionally, we consider ingredients to fit broadly into roles, for example protein, energy, macro- and micronutrients and added fat. However, not all nutrients are captured in a feed formulation. It is possible that we may extend the value of our ingredients even further by hoping that, and possibly designing for, our ingredients to fulfil multiple roles. For example, can an ingredient provide much-needed digestible protein but also support the animal's gut health, both of which will likely decrease unwanted emissions?

As ingredients and finished feeds become more technical in nature, we may be able to design them as such. There is precedent for this in finished feed. Over the last 50 years, feed formulation has become increasingly more complex. Domesticated chickens, for example, would originally have been fed a cereal alone. We moved to a formulated diet containing a cereal and a protein, with added fats and vitamins. More recently, we now include or ‘stack’ minor ingredients to improve gut health and performance. This stacking is relevant because we do this by including each ingredient individually. However, it may be that as we increase the level of design in protein ingredients, for example, we could engineer that they incorporate more than their basic nutrients. It is conceivable that a single cell protein could be developed on the basis of a target amino acid ratio and the presence of another key nutrient or functional ingredient, or indeed absence of a harmful constituent.

A key question to be considered is would consumers allow such an ingredient which is obviously beneficial but is ‘engineered’?

1.5 Conclusion

In our consideration of insects as a feed opportunity, the material would need to meet all the following criteria. They must: (i) be legal; (ii) have an acceptable and safe nutrient profile in relation to cost; (iii) be available in sufficient quantity; (iv) have attractive environmental impact criteria; and (v) have secured consumer acceptance. Insect products tick many of these boxes already but equally there are still some significant challenges that will be considered in subsequent chapters. These challenges may be solved by private enterprise but ultimately may need a coordinated and collaborative global approach to achieve success at scale.

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2 Which Insect Species and Why?

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2.1 Introduction

This chapter is focused on describing the common features determining the suitability of insects for small- and industrial-scale farming, the main insect species currently being produced on a large scale for feed production, as well as other potential candidate species. Natural consumption of insects by animals and which insects are suitable for which animal feed is also briefly discussed.

2.2 Common Features of Insects Reared for Animal Feed

Despite the huge diversity of insects, not all are suitable for use in animal feed or large-scale production, and currently research and development of industrial rearing systems for the production of animal and pet feeds is limited to just a few species. The major species produced worldwide include the Dipteran species black soldier fly (BSF; *Hermetia illucens*) and the common house fly (HF; *Musca domestica*), the Coleopteran species yellow mealworm (YM; *Tenebrio molitor*), and the Orthopteran crickets, locusts and grasshoppers (van Huis, 2016). In addition, differences in the legislation surrounding the use of insects in feed also impacts commercialization efforts: for example, current European Union (EU) legislation only permits certain insect species including BSF, HF, YM, lesser mealworm (LM; *Alphitobius diaperinus*), house cricket (HC; *Acheta domesticus*), banded cricket (BC; *Gryllodes sigillatus*) and field cricket (FC; *Gryllus* spp.), which have been reared on materials of vegetal origin in aquaculture feed, while for instance manure or catering waste is prohibited due to risks of pathogen transmission and toxin accumulation (European Commission, 2017). Meanwhile, there are fewer restrictions in Asia, Africa and America in terms of insect species and rearing substrates. For instance, BSF larvae are permitted in chicken feed in Canada (Sogari *et al.*, 2019).

Species currently farmed and under commercial development for industrial-scale production are characterized by short life cycles (Fig. 2.1), high feed conversion efficiency, amenability to mass rearing and their ability to grow at high densities on low value ‘wastes’

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(Makkar *et al.*, 2014). Key also is comparability of nutrient profiles to fishmeal and soya bean meal that make insects and processed products suitable for incorporation into compound feed although, like other feed ingredients, insect-derived products must not contain harmful levels of microbial or chemical contaminants. Insects such as BSF and HF are prone to bioaccumulation of heavy metals such as cadmium, lead, copper and zinc (Diener *et al.*, 2015; Gao *et al.*, 2019). To avoid bioaccumulation in the food chain, the quality of the rearing substrates must be monitored closely.

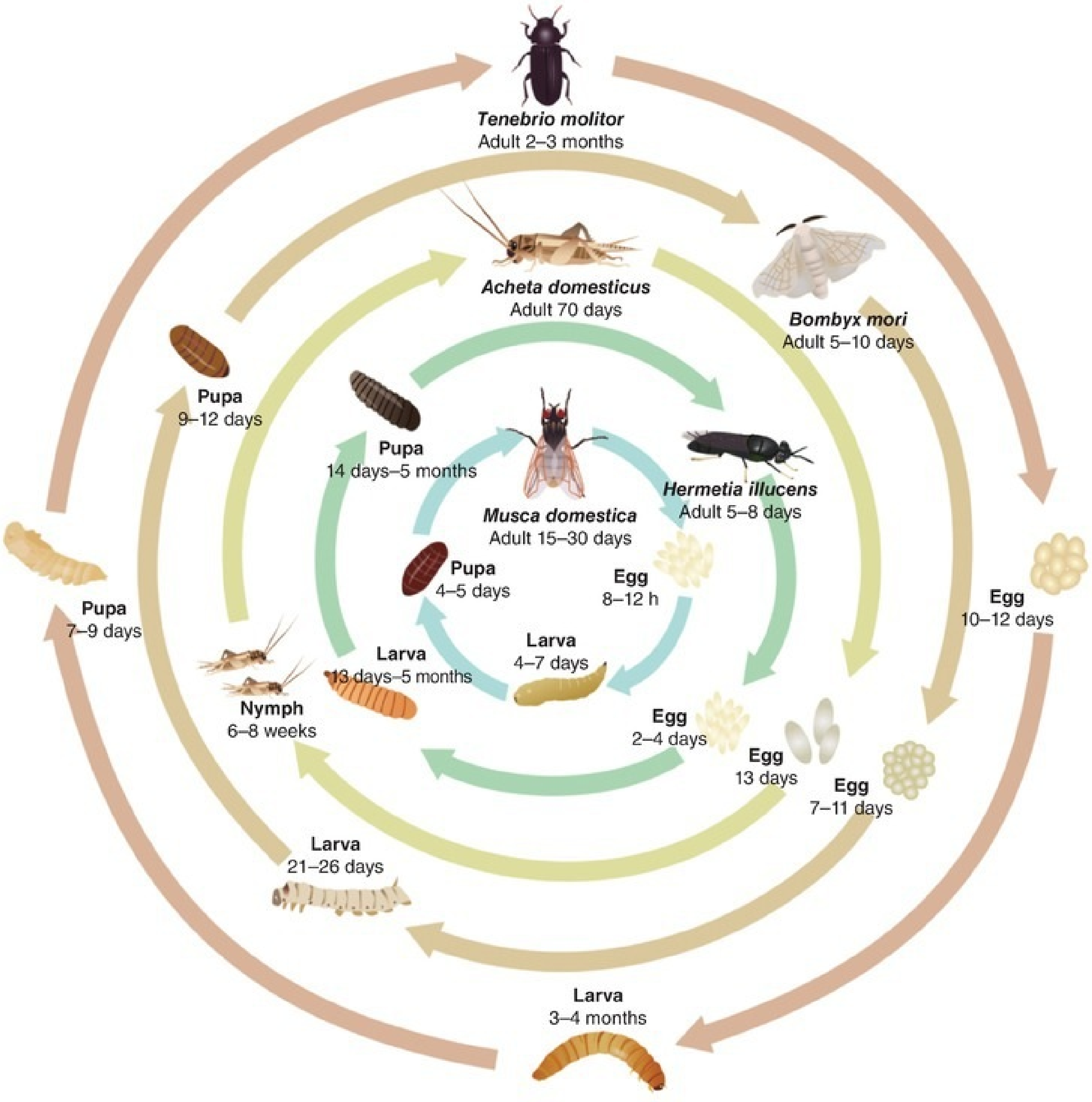

Fig. 2.1. Insect life cycles. The life stages of commonly domesticated insects, with the common house fly (*Musca domestica*) in the centre, followed by the black soldier fly (*Hermetia illucens*), the house cricket (*Acheta domesticus*), the silk moth (*Bombyx mori*) and yellow mealworm (*Tenebrio molitor*).

Different animal species vary in their nutritional requirements, in terms of amino acid profile, oil content and micronutrients, and these often change depending on the growth stage of the animal (Kim *et al*., 2019). While insects can be fed as a whole diet live or dried in small-scale farming scenarios, at industrial scale insect products are formulated alongside other raw materials and additives in compound feeds. The incorporation of insects into compound feed should not compromise but ideally should improve animal performance as compared to traditional feeds. Insect amino acid profiles are suitable for monogastric animals and fish, prawns and shrimp as they require high levels of protein and, unlike ruminants, are unable to synthesize all the essential amino acids (Riddick, 2013; Makkar *et al*., 2014; Henry *et al*., 2015; Cummins *et al*., 2017; Digiacomo and Leury, 2019). On the contrary, soya bean meal often requires amino acid supplementation when used in feed for monogastric animals (Parolini *et al*., 2020).

Insect rearing involves cultivating the species from eggs to larvae (or nymphs) to adults. Usually, an adult breeding culture is maintained separately from larval production to obtain eggs (Makkar *et al*., 2014). Smallholder farmers in Africa do, however, use natural oviposition systems, for example by placing crop residues on small termite nests to increase termite populations, or attracting flies for maggot production by exposing organic waste substrates (Kenis *et al*., 2014) (Fig. 2.2). For farming to be feasible, the insect must be reared easily and at an economically and environmentally sustainable cost. In lower income countries, for example in the Asia Pacific region and Africa, where labour is relatively cheap, smaller scale farming systems are cheap to establish, and typically involve single-cage farming to supply subsistence products for individual farmers (Kenis *et al*., 2014; Yen, 2015). By contrast, larger scale and increasingly automated systems are seen as essential in higher-income countries where labour costs are higher and feed supply chains may be more centralized. Large-scale rearing requires optimization of the rearing conditions (temperature, humidity and rearing substrates) to shorten developmental times allowing more generations per year, increased biomass conversion efficiencies (i.e. waste to insect biomass) and thereby increased productivity (Makkar *et al*., 2014).

Fig. 2.2. Termite trap in a poultry farm in Burkina Faso. Photo courtesy of CABI.

2.3 Insects Species Reared at Large Scale

Black soldier fly

The Dipteran species BSF, *H. illucens*, is native to America and now widespread in tropical and warmer temperate zones between 45°N and 40°S (Diclaro and Kaufman, 2009). Dense populations are commonly found growing in the manure of poultry, pigs and cattle and other organic wastes, for example rotting fruits and vegetables (van Huis *et al*., 2013). BSF larvae (BSFL) are high in protein and fat, with approximately 35–57% crude protein and 35% crude oil (dry weight) (Veldkamp *et al*., 2012). Their lauric acid levels are high, ranging from 16% to 70% of the total fat content (Liu *et al*., 2017). BSFL are thus able to efficiently convert a wide range of 'waste' streams into high-value protein and fat while reducing the mass, moisture and odours of the waste (Makkar *et al*., 2014).

BSF tolerate a range of rearing conditions, although temperature and diet quality have a large impact on the life cycle length. Ideal rearing conditions for larvae are between 29°C and 31°C with a humidity of 50–70% (Makkar *et al*., 2014) whereas adults can be reared between 27.5°C and 37.5°C (Veldkamp *et al*., 2012). Adult flies are reared separately and each female oviposits once and can lay 206–1088 eggs (Tomberlin *et al*., 2002; Samayoa *et al*., 2016). BSF eggs hatch 2–4 days after oviposition, and the larval stage may last 14 days to 4 months, pupation lasts between 14 days and 5 months and the adult female flies mate 2 days after they emerge (Diclaro and Kaufman, 2009; Makkar *et al*., 2014). In nature, larvae feed within the moist, organic substrate and subsequently migrate to a dry site to pupate (Liu *et al*., 2017). At the point of harvest, larvae can weigh up to 220 mg (Tran *et al*., 2015). Their migratory behaviour can be exploited, as larvae self-harvest by migrating into a collection vessel as they seek to find a location to pupate (Makkar *et al*., 2014).

As adults BSF do not feed, they are not vectors of disease and this is an important facet of feed and food safety (van Huis *et al*., 2013). The choice of substrate affects the duration of the rearing cycle, sustainability, the performance of the flies, as well as their final nutritional content (Gold *et al*., 2020).

Common house fly

HF, *M. domestica*, is globally the most common Dipteran species being most frequently found in tropical environments on manure and decaying organic waste. The flies require a humid and warm environment, ideally over 25°C (Diehl *et al*., 2014). Their life cycle is short, with eggs hatching 8–12 h post-oviposition, the larval stage lasting 4–13 days, but typically 5 days at optimal conditions, and pupation lasts 4–5 days (Sanchez-Arroyo and Capinera, 1998). As with BSFL, they grow in dense populations and the length of the cycle is highly dependent upon rearing conditions. The combined larval and pupal stage can be reduced from 10 to 6 days under optimized conditions at 32–38°C, 50–70% humidity and a substrate of decaying organic matter (Diehl *et al*., 2014; Makkar *et al*., 2014). The number of eggs laid per female can also be increased from 500–600 up to 2000 by optimizing rearing conditions (Heuzé and Tran, 2015). HF larvae develop more quickly than BSFL, but they are much smaller with pupae weighing approximately 18 mg compared to BSF pupae of 153–

156 mg (Barnard and Geden, 1993; Shumo *et al.*, 2019). As compared to BSF, HF are easier to rear and they tolerate colder temperatures and drier climates. HF larvae typically have higher protein contents than BSFL, at 43–68% crude protein (dry weight), and crude oil ranges from 4% to 32% (dry weight) (Veldkamp *et al.*, 2012).

Houseflies are adapted to feeding on bacteria and fungi and smaller particles than BSF, and while they are most commonly reared on animal manures they can feed on vegetal wastes and desiccated *Escherichia coli* or yeasts (Levinson, 1960; Haupt and Busvine, 1968; van Huis *et al.*, 2020). A major drawback for large-scale HF rearing is that the adults feed and are known to transmit over 100 infectious diseases (van Huis *et al.*, 2020). Unlike adult BSF, adult HF are drawn to human and animal habitats. The larvae themselves may harbour microbes from the rearing substrate and this raises potential issues for safe use as animal feed especially when, as occurs in rural Africa, larvae are fed live, directly to poultry and fish (Awoniyi, 2007; Kenis *et al.*, 2014). Gut clearance and processing methods such as heat treatment, commonly used for other feed ingredients have, however, been shown to mitigate potential microbiological risks (Hall *et al.*, 2018).

Mealworm

Larvae of the Tenebrionidae beetle species *T. molitor* and *Tenebrio obscurus* are commonly known as yellow and mini mealworm, respectively. These beetles are native to Europe, but are found worldwide (Makkar *et al.*, 2014). Industrial-scale production of mealworms is already established, mainly for wild bird, pet and zoo animal feed, as they are relatively easy to rear and have good nutritional value, suitable for use in poultry feed (van Huis *et al.*, 2013). The LM, *A. diapernius*, and the superworm (SW), *Zophobas morio*, are reared for reptile and amphibian pet feed (van Huis, 2020). Mealworm larvae typically contain 44–69% (dry weight) crude protein and 23–47% (dry weight) crude oil (Veldkamp *et al.*, 2012). Additionally, they provide good sources of zinc and magnesium, while being relatively low in calcium (Grau *et al.*, 2017).

The larvae are sold live, dried, canned or as a powder for feed (Veldkamp *et al.*, 2012). Ideal rearing conditions are colder than for the flies, at 18–25°C and life cycle duration typically lasts 250–360 days depending on rearing conditions (Makkar *et al.*, 2014). The egg stage lasts 10–12 days, and larval maturation normally takes 3–4 months. They pupate for 7–9 days, and adult beetles live for 2–3 months. Mealworms are omnivorous, and, like BSF and HF, can be reared on organic plant or animal wastes (van Huis *et al.*, 2013). Traditionally, their commercial diet has, however, consisted of cereal bran or flour supplemented with protein (Makkar *et al.*, 2014). As with HF, there is a risk of microbial transmission when using mealworms in feed, but microbial load has been shown to be significantly reduced by heating or bleaching of the larvae (Grau *et al.*, 2017).

Crickets, locusts and grasshoppers

More than 20,000 insect species belong to the order Orthoptera, including crickets, locusts and grasshoppers (Ayieko *et al*., 2015). These are generally edible, and many are commonly consumed by humans in Africa, South America and Asia (van Huis *et al*., 2013). Locusts, crickets and grasshoppers have typically been harvested from the wild, where they feed on grass, crops and leaves, but domestication is possible (van Huis *et al*., 2013). For instance, long-horned grasshoppers may be reared in netted enclosures (Ayieko *et al*., 2015) and grasshopper rearing at industrial scale is being developed for use in animal feed in South-east Asia.

Crickets, locusts and grasshoppers have three life stages: (i) eggs; (ii) wing-less nymphs; and (iii) adults (Ayieko *et al*., 2015). In nature, females oviposit in soil, and lay 'pods' containing dozens of eggs during the winter, these hatch in warmer spring temperatures (Ayieko *et al*., 2015). The maturation time of nymphs is highly dependent on the species and the rearing temperature. Adults become sexually mature after a few weeks. In cold climates, the egg stage may last up to 9 months, and the nymph and adult stage lasts up to 3 months.

Commercial rearing of HCs (*A. domesticus*) is optimal at 30°C and 50–70% humidity; under these conditions a full life cycle can be completed in 8 weeks (Ayieko *et al*., 2015). In comparison, at 18°C the life cycle can last up to 8 months. Locusts, crickets and grasshoppers generally require: (i) a moist, dark place to oviposit; (ii) a diet consisting of leaves alternatively supplemented with wheat germ, vegetables, fruit or in some cases chicken mash; and (iii) an available water source.

2.4 Other Insect Species as Potential Candidates

Silkworms

The Lepidopteran silkworm, *Bombyx mori*, was domesticated approximately 5000 years ago due to its production of valuable silk (Xiang *et al*., 2018). Silk is derived from the raw silk cocoons produced when the moths pupate, and this process yields large amounts of spent silkworm pupae (Patil *et al*., 2013). Silkworm pupae are consumed by humans in silk-producing countries (China, India and Thailand) and contain approximately 60% crude protein and 25% fat on a dry weight basis (Makkar *et al*., 2014). The high protein level makes them good candidates for use in animal feed, especially when processed to remove the oil. The environmental impact of silk production may be reduced by utilizing this major by-product (Patil *et al*., 2013; Sheikh *et al*., 2018).

The silkworm moth has four life stages: egg, larvae, pupae and adult lasting approximately 7–11, 21–26, 9–12 and 5–10 days, respectively (Gurjar *et al*., 2018). The complete life cycle lasts between 6 weeks and 9 weeks. Females begin oviposition 5.5–8.5 h after emergence, and they lay approximately 350 eggs in their lifetime (Diehl *et al*., 2014). Industrial rearing of silkworms is well established. The environmental requirements for silkworm rearing are 24–27°C and 70–90% humidity (Krishnaswami, 1978). Silkworms are typically fed with leaves (mulberry leaves for *B. mori*), and their growth and development depends on the quality of their diet (Krishnaswami, 1978). It is also important that they are given sufficient space, as their growth and fecundity is reduced if the density is too high (Krishnaswami, 1978). The need for relatively low rearing densities and preference for a relatively expensive diet of mulberry leaves reduces the suitability of this species for large-scale rearing for animal feed (Diehl *et al*., 2014).

Termites

The Isopteran insect termites, in particular *Macrotermes* species, constitute 3% of global insect consumption by humans (Anankware *et al*., 2015). These are typically harvested from the wild, for example by beating the ground around the termite hills, which forces them to emerge, or by 'fishing' them out of their nests by getting them to bite on to a stick or leaf (van Huis *et al*., 2013). The insects are rich in protein, fats and micronutrients, thus can function as a valuable supplement in the diet (Adepoju, 2020) but are also used as fish bait in Zambia (Silow, 1983) and are used in poultry feed in West Africa (Kenis and Hien, 2014). A 50% replacement of fishmeal with termite meal is suitable in the diet of the catfish *Heterobranchus longifilis* (Sogbesan and Ugwumba, 2008). Large-scale production of termites is not generally considered sustainable due to the difficulty of rearing and their high levels of methane production, a by-product of the symbiosis with the bacteria present in termite (Anankware *et al*., 2015).

Cockroaches

Blattodean species include the cockroaches, which are known for being resilient, adaptable to a range of environmental conditions and for their quick population growth (Diehl *et al*., 2014). For instance, the Madagascar cockroach *Gromphadorhina portentosa* is reared at temperatures 23–26°C and 30% humidity, at which nymphs mature in 3 months (de Carvalho *et al*., 2019). Meanwhile, the death's head cockroach *Blaberus craniifer* is reared at 25–30°C and 65–80% humidity (Diehl *et al*., 2014). Vegetable and fruit waste substrates can be used for cockroach rearing. *G. portentosa* contains approximately 67% (dry weight) crude protein and cockroach meal has been found to be a suitable protein source for cockatiels when included in the diet at 6.6% (de Carvalho *et al*., 2019). Potential issues with industrial-scale rearing and commercial use of cockroaches is their methane production and potential to transmit pathogens such as *E. coli* and *Salmonella* species (Diehl *et al*., 2014).

Mopane worm

Imbrasia belina, a Lepidopteran moth native to southern Africa, is an important protein source for local populations (Madibela *et al*., 2008; Okezie *et al*., 2010). The larvae have a high nutritional content with 47–56% crude protein and 16–18% crude fat (dry weight), and an amino acid profile comparable to fishmeal and soya bean meal (Makhado *et al*., 2014). Currently, worms are wild harvested from mopane trees in Botswana and sold locally, or exported to South Africa for selling as human food or processing into livestock feed (Madibela *et al*., 2007). However, studies on the suitability of mopane worms in animal feed are limited.

2.5 Which Insect for Which Animal?

Insects constitute a natural part of the diet for many animals, most particularly birds and fish (van Huis *et al*., 2013). Incorporation of these insects in the diet of domesticated animals (as depicted in Fig. 2.3) therefore seems appropriate as they are, in the main, adapted to feed on insects. Pigs are omnivores and naturally exhibit foraging behaviour in the wild consuming mainly plant materials such as leaves and fruits, but also fish and invertebrates including beetles, earthworms and insect larvae (Jakobsen *et al*., 2015). Wild birds and free-range poultry also naturally feed on soil-borne insect larvae and worms (Clark and Gage, 1996). Both freshwater and saltwater fish consume insects, especially during the juvenile life stages. Examples of extensive consumption include catfish species such as the African catfish, *Clarias gariepinus* and the common catfish, *Ameiurus melas* which consume insects, and the Atlantic salmon, *Salmo salar* which feeds on aquatic insect species (Henry *et al*., 2015).

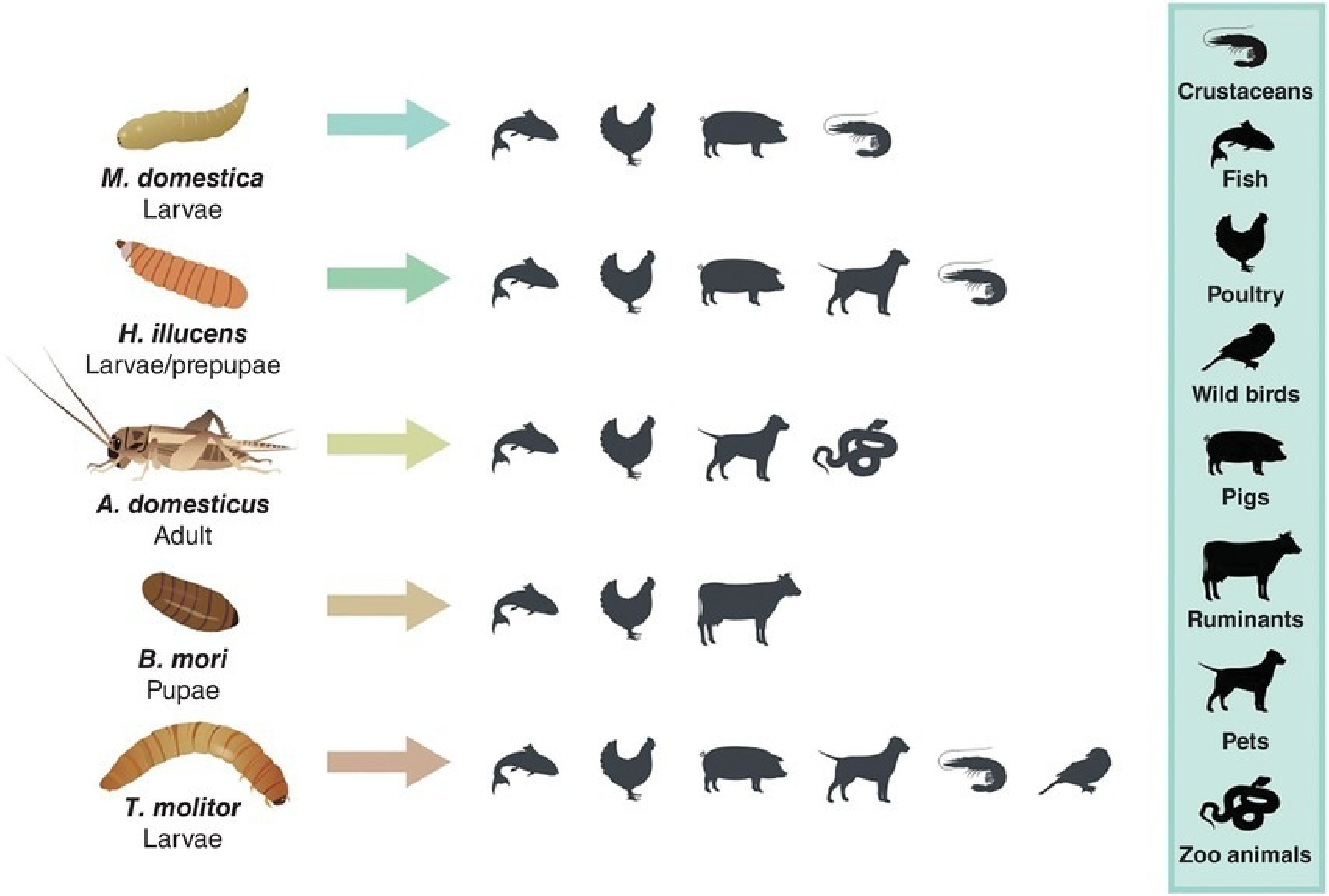

Fig. 2.3. Which insect for which animal? Depicting suitability for inclusion of HF, BSF (larvae and prepupae), cricket (adults), silkworm (pupae) and mealworm in the diets of crustaceans, fish, poultry, wild birds, pigs, ruminants, pets and

exotic/zoo animals.

Although mass rearing for feed is relatively new, insects have been reared for exotic pet and zoo animal feed for decades (van Huis *et al.*, 2013). Mealworms and crickets are the most common species, and are reared in Asia, North America and Europe. Over 100 t of YM are produced annually in China, and there is a large industry for rearing YM, LM and the SW in the Netherlands for reptile, avian and fish feed (Zhang *et al.*, 2008; van Huis *et al.*, 2013). Mealworms can be fed to cats and amphibians too. Crickets are also extensively used, and billions are sold live in America per year to pet stores for reptiles and fish (Weissman *et al.*, 2012). Crickets have also been found suitable as a potential ingredient in dog food (Jarett *et al.*, 2019). In 2019, the pet food brand In Yora Pet Foods launched a dog food where 40% of the protein comes from BSFL.

Insects differ in their amino acid profiles, fat, crude protein and micronutrient content. Most insects currently reared at scale, flies and mealworms in particular, have been shown to have a suitable amino acid profile for feeding to monogastric animals, fish, prawns and shrimp (reviewed by Veldkamp *et al.*, 2012; Makkar *et al.*, 2014; Anankware *et al.*, 2015; Henry *et al.*, 2015; Sheikh *et al.*, 2018; Digiacomo and Leury, 2019). The nutritional contents of insect vary depending on their life stage, for example the chitin content usually increases in pupae and adult insects compared to larvae, and each type of insect requires specific processing and preparation (Halloran *et al.*, 2018). Some insects, such as mealworms may be fed live, while others are dried, roasted, chopped, defatted, ground or processed to improve chitin digestibility (Henry *et al.*, 2015). Ruminant nutritional requirements are met by both digested feed protein and protein provided by symbiotic rumen microbes, and as generally ruminants are fed on low-protein diets, insects have not been widely considered for use in ruminant diets (Abbasi *et al.*, 2018).

2.6 Conclusion

In the coming years, further animal feeding trials, ongoing optimization of industrial rearing systems, and perhaps an expansion of the number of suitable species will help us to realize the potential for the adoption of insects and insect products for animal feed. Historical use together with technology advances, evidence-based legislative changes and consumer perception are likely to collectively drive the expansion of production outputs to different extents across distinct geographical locations. Overall, there seems little doubt that insect-based feeds will become increasingly important as the global demand for animal feed, and particularly animal protein, rises.

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3 Insect Products, Processing and Safety

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3.1 Introduction

Interest in use of insects for animal feed purposes has gained increasing attention as alternative sources of protein which are sought together with sustainable production methods. The focus at both research and commercial production levels has primarily been on larvae and prepupae of the black soldier fly (BSF), *Hermetia illucens* and larvae of the yellow mealworm (YM), *Tenebrio molitor*. Larvae of the house fly (HF), *Musca domestica*, and the lesser mealworm (LM), *Alphitobius diaperinus*, have also been extensively researched. In addition to protein, the main products that can be obtained from insects are fats/oils and chitin. There is also evidence for production of functional molecules such as antimicrobial peptides (AMPs) and antioxidants by these and other insect species.

The amount of protein, fat and chitin will vary between species and between different developmental stages (Makkar *et al.*, 2014). The composition of the protein, in terms of amino acid profile, and the fats, in terms of the fatty acid profile, will also vary (Makkar *et al.*, 2014). Protein and fat quantity and fat quality can also be affected by the substrate on which the insect larvae are reared (Spranghers *et al.*, 2017) and by the downstream processing methods.

Generally, insect processing begins with separation of the appropriate developmental stage from the feeding substrate followed by a killing method, which may include heating, freezing, drying and maceration. Some of these methods, for example heating, can also act as a pasteurization stage, reducing the number of microorganisms that are present. However, the processing method used can affect the quality of the protein and fat in the final products (Caligiani *et al.*, 2019; Leni *et al.*, 2019; Montevecchi *et al.*, 2019).

Following the kill step the larvae may be dried and ground to a powder to form an insect meal that can then be formulated into animal feed. Alternatively, further processing can take place to separate the protein, lipid and chitin (Fig. 3.1). This additional downstream processing increases costs, but this may be outweighed by the benefits of products with greater purity or consistency for easier inclusion into feed formulations (Dumas *et al.*, 2018) or use in other industries, such as the oil fraction for biodiesel. A reduction in the fat content and a higher protein level aids the use of defatted insect meal in pelleted formulations and reduces the risk of fat oxidation when the resulting product is stored (Dumas *et al.*, 2018).

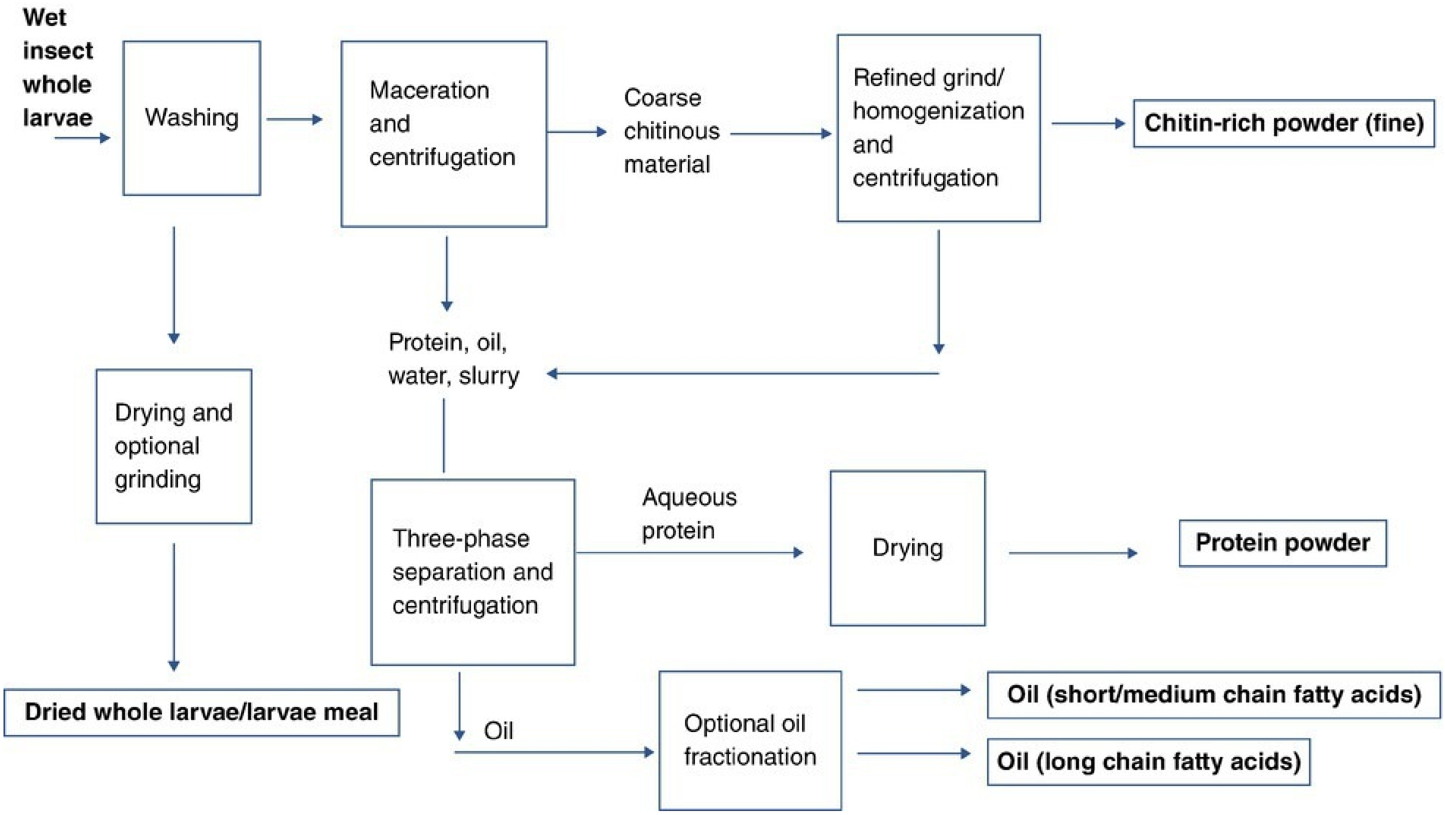

Fig. 3.1. Overview of insect processing for production of protein, oils and chitin.

Methods for separation of the products may involve mechanical, chemical or biological (enzymatic) extractions. The processing method used can affect the nutritional properties of the resulting insect products, as well as the colour of the insect meal due to enzymatic processes catalysed by phenoloxidase and the presence of iron, which forms iron–phenolic complexes resulting in undesirable colour formation (Janssen *et al.*, 2019; Larouche *et al.*, 2019).

While many of the processing methods are based on those commonly found in the food and feed processing industries, commercial companies have also developed proprietary methods for processing insects and patents have been filed for some of these methods (e.g. Pipan, 2020). Research is ongoing to investigate extraction methods that can improve the overall yield or purity of the resultant products, and/or the sustainability of the process itself.

It is essential to ensure that the insect products, either the whole insect meal or the separated fractions, are safe for use. The risk of contaminants in the final products will depend on the substrate that is used to rear the insects and the production and processing methods. Depending on the end use of the products different regulations may apply. These regulations will also differ depending on the country of production and the global market in which the products will be used.

The following sections describe commonly used processing methods and method development to improve the yield and purity of the products. Factors that affect the safety of the products are also considered. The focus of this chapter is primarily on BSF, but the processing and safety considerations are similar for other insect species and where differences are observed this is highlighted.

3.2 Insect-derived Products

The processing method used to separate insect protein, oil and chitin affects the yield and purity of the products obtained, but is evaluated against the cost of the process to achieve a commercially marketable product. Methods have been developed for sequential extraction of all three products (Caligiani *et al*., 2018; Smets *et al*., 2020). For example, Smets *et al*. (2020) reported on studies for three life stages (larvae, prepupae and pupae) of BSF using a sequential method based on oil extraction with petroleum ether, extraction of protein via solubilization (pH 11) and precipitation (pH 4) and further purification of the impure chitin with hydrochloric acid and sodium hydroxide. Other methods have focused on obtaining a single component. Most of the studies, however, have been made at a laboratory scale and there are few publications that examine commercial-scale activities, likely due to commercial sensitivities and cost implications.

Protein

Protein can be extracted using mechanical, chemical or enzymatic methods. The amino acid profile in protein from BSF larvae and prepupae does not differ significantly when the insects are reared on different substrates (Spranghers *et al*., 2017). However, the method used to kill the larvae has been shown to affect the nutritional profile and extractability of the protein. Blanching rather than freezing facilitates the separation of proteins from other molecules and prevents the loss of essential amino acids, likely due to the denaturation of enzymes (including insect-derived proteases) involved in melanization and other processes (Leni *et al*., 2019).

Caligiani *et al*. (2018) reported that an alkali extraction provided best separation of the protein (96% recovery) but this process resulted in damage to the protein as indicated by the degree of hydrolysis, thereby reducing digestibility. Using milder conditions and based on the Osborne fractionation method (Osborne, 1907) protein recovery was reduced but more than 85% of protein was recovered, and this was of high quality, with negligible hydrolysis (Caligiani *et al*., 2018). This was also compared to an enzymatic assisted method, which gave 60% protein recovery (Caligiani *et al*., 2018).

An enzymatic extraction process was also evaluated at a laboratory scale by Leni *et al*. (2020). Commercially available proteases were used to improve protein extraction. This resulted in the production of protein hydrolysates and showed an average 20% increase in solubilized protein when enzymes were present compared to extraction in the absence of the enzymes, resulting in an average extraction yield from BSF larvae of 71 ± 8% and 67 ± 6% from LM larvae (Leni *et al*., 2020). The enzymatic process also resulted in the release of free amino acids, which are considered more available from a nutritional perspective than bound amino acids (Leni *et al*., 2020).

Fats

The fat derived from BSF is of high quality compared with plant and animal oils. BSFs are high in lauric acid, which is a medium chain fatty acid (C12:0) that is more easily digested than longer chain fatty acids and has antimicrobial activity (Spranghers *et al.*, 2017). BSF fat can also be used to produce biodiesel which, following a two-step procedure on the extracted oil, has been shown to conform to current quality standards (EN14214) (Li *et al.*, 2011).

The method used to kill the insect has been shown to affect the composition of the fat when the insects are stored. Blanching resulted in a lipid fraction composed mainly of triacylglycerols that after 2 months of frozen storage was similar to the initial composition. In contrast, for lipids extracted from frozen prepupae there was a reduction in acylglycerols and a release of free fatty acids (Caligiani *et al.*, 2019). It was reported that the difference was likely due to thermal denaturation of lipases during the blanching process (Caligiani *et al.*, 2019). This observation could have implications for the final use of the lipid where quality and consistency are paramount.

Fats are generally separated by solvent extraction and a study by Ravi *et al.* (2019) examining green (biomass-derived) solvents for defatting of BSF larvae, concluded that 2-methyloxolane was a good candidate to replace n-hexane, a commonly used petrochemical solvent.

Chitin

Chitin is composed of *N*-acetyl-D-glucosamine sugars linked with β 1–4 glycosidic bonds (Rinaudo, 2006) (Fig. 3.2) and in insects, it is a component of the exoskeleton and peritrophic matrix (Zhu *et al.*, 2016). Chitosan, the deacetylated derivative of chitin is produced once the chain consists of more D-glucosamine components than *N*-acetyl-D-glucosamine. The proportion and distribution of the different sugar residues and the length of the chains leads to differences in antimicrobial, haemostatic, antioxidant and anticholesterolemic properties (Aranaz *et al.*, 2009). This range of different properties has led to a wide variety of applications making this family of molecules and possible new purification strategies extremely valuable.

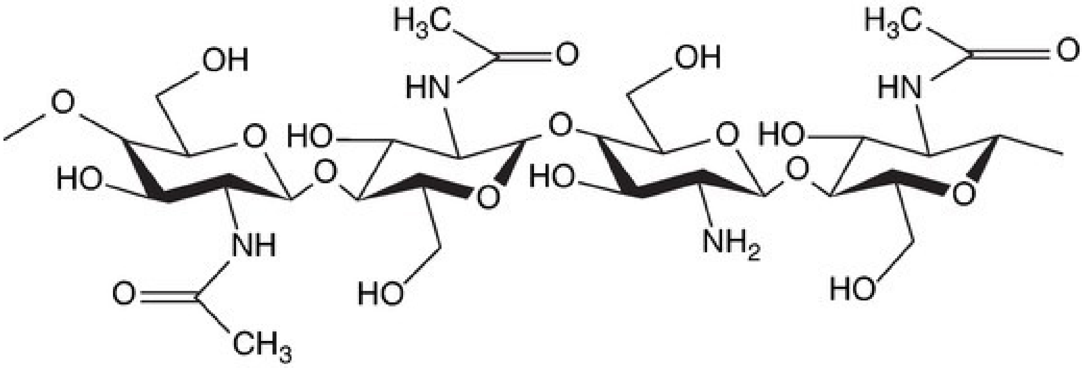

Fig. 3.2. The optical structure of chitin.

In insect processing, after separation of the protein and fat, a chitin purification step can be performed. Chitin purification methods commonly involve treatment with an acid and an alkali to remove minerals and proteins, respectively (Liu *et al.*, 2012; Waśko *et al.*, 2016). However, this can be substituted for alternatives such as enzymatic extractions, ionic liquids or deep eutectic solvents (Qin *et al.*, 2010; Zhang *et al.*, 2017; Zhou *et al.*, 2019).

Antimicrobial peptides (AMPs)

AMPs are small peptides that can exhibit a broad range of antimicrobial activities. More than 150 insect-derived proteins with antimicrobial activity have been identified to date (Gasco *et al.*, 2018).

Isolation and characterization of a novel AMP from the haemolymph of BSF larvae following induction was described by Park *et al.* (2015). This was a defensin-like peptide 4 (DLP4) with activity against Gram-positive bacteria including methicillin-resistant *Staphylococcus aureus* (MRSA). It has subsequently been shown that BSF larvae have approximately 50 genes that encode AMPs and that diet can affect the expression of these genes (Vogel *et al.*, 2018). AMPs with activity against Gram-negative bacteria (Park and Yoe, 2017) and *Helicobacter pylori* (Alvarez *et al.*, 2019) have also been identified from BSF following induction by injection of *S. aureus* and *Escherichia coli*, respectively.

Although it has been demonstrated that BSF larvae express proteins with antimicrobial properties, it is not yet clear how these could be produced at scale as a potential alternative to antibiotics. It has also not been demonstrated whether the presence of these peptides has an effect when insect meal or purified protein is incorporated in animal feed or whether the processing steps would destroy any potential activity.

Antioxidants

Antioxidants are molecules which inhibit or reduce oxidation, a process which can increase the levels of free radicals that can cause cell and DNA damage. Antioxidants are therefore perceived as compounds positive to animal and human health. Hydrolysates derived from protein extracted from BSF larvae have been shown to have antioxidant properties and it is proposed that these could have potential for use in the pharmaceutical industry or in functional foods and feed (Zhu *et al.*, 2020).

3.3 Safety of Insect-derived Products

Ensuring the safety of insect-derived products for use in food and feed applications is critical. Contaminants can be introduced from the environment in which the insects are reared (e.g. from air and water sources) or from the substrates on which the insects are grown. Contaminants can include chemicals (e.g. heavy metals, mycotoxins, pesticides, dioxins) and biological sources (e.g. bacteria including *Salmonella* spp. and *Bacillus cereus*). The potential for allergenicity should also be considered.

Chemical safety

Chemical contaminants accumulating in the insects from the substrates they are reared on include pesticides, heavy metals, mycotoxins, dioxins and polychlorinated biphenyls (Charlton *et al*., 2015; Purschke *et al*., 2017; van der Fels-Klerx *et al*., 2018). Raising insects in controlled environments offers several opportunities to minimize these risks. Through controlling the feed substrate it is possible to limit the chemicals and microorganisms that the larvae will come in contact with (Schlüter *et al*., 2017).

Studies have shown that some insect species, including BSF, can bioaccumulate certain heavy metals, in particular cadmium (Charlton *et al*., 2015; Purschke *et al*., 2017). Diener *et al*. (2015) reported bioaccumulation of cadmium in larvae and prepupae of BSF when reared on chicken feed pellets spiked with three different concentrations of cadmium, the lowest being equivalent to 2 µg/g in feed (the European Union (EU) limit for cadmium in animal feed from feed materials of animal origin). In that study lead and zinc were also spiked in the feed and although both metals were present in larvae, prepupae and adults, no bioaccumulation was found. The presence of the heavy metals did not affect the development of the BSF, but it was observed that the mass of the prepupae on a dry weight basis was significantly greater than the control when reared on the feed containing cadmium.

BSF larvae reared on a plant-based diet incorporating different levels of seaweed (0–100% in 10% increments) were found to accumulate cadmium, lead, mercury and arsenic, but the degree of accumulation of cadmium was greater than for the other metals (Biancarosa *et al*., 2018). Levels of lead and mercury were only slightly higher than those found in the feed indicating a relatively low accumulation of these metals compared to cadmium (Biancarosa *et al*., 2018). Arsenic had the lowest retention in the larvae of the metals tested, but the arsenic levels, together with those for cadmium, exceeded the maximum permitted levels in complete feed under EU Directive 2002/32/EC (0.5 mg/kg and 2 mg/kg for cadmium and arsenic, respectively) for larvae reared on diets with 20% or greater seaweed inclusion (European Commission, 2002).

Bioaccumulation of cadmium, but not chromium was also observed in studies by Gao *et al*. (2017) examining both the effect on development and the presence in different life stages. These authors demonstrated that cadmium was found in the exuviae of the prepupae providing a potential method to recover cadmium from insects reared on contaminated substrates (Gao *et al*., 2017). These authors also found that in the larvae and prepupae of BSF, cadmium was found in the the body rather than the integument. This finding led Biancarosa *et al*. (2018) to suggest that as cadmium was found mainly in the body of the larvae, it was more likely that the cadmium would be present in extracted protein due to the higher affinity to protein rather than fat.

Accumulation of cadmium could also be a problem for HF larvae (Charlton *et al*., 2015), arsenic in YM (van der Fels-Klerx *et al*., 2016) and lead may also need to be monitored in

BSF (van der Fels-Klerx *et al*., 2016; Purschke *et al*., 2017). Therefore, regular contaminant monitoring of the substrate and larval biomass is necessary to ensure these do not reach unsafe levels in the feed and food chain (Purschke *et al*. 2017).

It has been suggested that as insect species show different abilities to accumulate and metabolize heavy metals, different maximum levels in the rearing substrate should therefore be recommended for each species (Schrögel and Wätjen, 2019).

Studies have demonstrated that BSF larvae do not bioaccumulate mycotoxins from the rearing substrate (Bosch *et al*., 2017; Purschke *et al*., 2017; Camenzuli *et al*., 2018) and in general the levels of mycotoxins found in the larvae in these studies were very low or below the limit of quantification. Studies conducted by Fera Science Ltd have shown the presence of emodin and sterigmatocystin in BSF larvae reared on plant material in which these mycotoxins were present (unpublished data).

LM have been shown to metabolize certain mycotoxins (Purschke *et al*., 2017; Camenzuli *et al*., 2018) and can also degrade some pesticides (Lalander *et al*., 2016; Purschke *et al*., 2017). In addition, aflatoxin B1 was shown not to bioaccumulate in YM (Bosch *et al*., 2017). However, studies that have examined mass balance have shown that not all of the material could be accounted for, either as the native mycotoxin or known metabolites, and therefore further research into understanding the degree to which these species can metabolize mycotoxins will help in applying chemical safety criteria (Camenzuli *et al*., 2018).

Microbiological safety

Potentially harmful organisms are often present in the natural environment in which insects develop. These include bacteria, fungi, viruses and other parasites (Schlüter *et al*., 2017). Larvae and prepupae of BSF can harbour high levels of microorganisms and this can depend on the substrate on which they have developed. Therefore, development of post-harvest treatments to minimize the populations of harmful organisms is essential to meet feed safety regulatory requirements. These may need to be specific to the insect species and substrate they are reared on (Schlüter *et al*., 2017; Caparros Megido *et al*., 2018).

Heat treatment and high-pressure processing are methods that are commonly used to eliminate pathogenic organisms. In a study to compare the effect of heat treatment and high-pressure processing on BSF larvae it was demonstrated that thermal processing (heating to 90°C for 10 or 15 min) was more effective than high-pressure processing (400 or 600 MPa for 1.5 or 10 min) in reducing the total viable count (Campbell *et al*., 2020). Heat treatment at 90°C for 10 or 15 min and high-pressure processing at 600 MPa reduced levels of *Enterobacteriacae*, lactic acid bacteria and yeast and mould count below the limit of detection (Campbell *et al*., 2020). Heat treatment had no reported effect on the calculated *in vitro* digestibility, but the heat-pressure processing showed increased ruminal digestibility and decreased monogastric digestibility (Campbell *et al*., 2020).

If larvae still contain feed and frass in their gut when they are killed this could impact on the subsequent microbial load and a feed withdrawal period for edible insects has been recommended (van Huis *et al*., 2013). However, it has recently been demonstrated that a feed withdrawal period of up to 96 h did not reduce the microbial load of BSF larvae when reared on the Gainesville diet, a commonly used artificial diet for BSF larval development (Larouche, 2019).

Sterilization and lactic acid fermentation show promise for maintaining safe levels of endospores but this needs further development to understand how these methods affect the insect nutritional profile (Caparros Megido *et al*., 2018; Garofalo *et al*., 2019).

Allergenicity

Allergenic responses can occur in both humans and animals. The majority of allergens are proteins and it is known that some allergens are present in insects. Tropomyosin, arginine kinase and myosin light chain from BSF have shown sequence homology to known allergens, indicating that these are also potentially allergenic (Romero *et al*., 2015). Most studies on allergenicity have focused on insect species used as food, but there are still only limited studies in this area and potential allergenic effects in animals are poorly studied. The effect of processing on the potential for allergenicity also needs to be assessed as a possible mitigating factor (van der Fels-Klerx *et al*., 2018).

3.4 Conclusion

Methods used for downstream processing of insects will depend to some degree on the insect species, the final products required and the markets for those products. Processing to date has used methods commonly practised throughout the food and feed processing industries, but modifications to these methods or the use of novel methods are being explored, albeit currently on a laboratory scale. Commercial companies may have enhanced and improved these methods, but this data is protected by commercial sensitivities. The processing methods must provide a commercially economic means of generating the required products at an appropriate yield and quality. In industrialized processes it is critical that Hazard Analysis and Critical Control Point (HACCP) principles are employed to maintain the safety of the insect products.

Within this nascent industry more research for insect-specific processing methods and evaluation of the feasibility of extracting or producing novel compounds such as AMPs and antioxidants from insects is needed. Further downstream processing of the products, for example methods to convert insect oil into biodiesel, may also be beneficial.

There is a need for a legislative framework with criteria for trading, hygiene standards and microbiological safety (Garofalo *et al*., 2019; Frigerio *et al*., 2020) and this may provide an option to extend the range of permitted substrates to rear insects, subject to comprehensive safety assessments.

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4

Suitability of Insects for Animal Feeding

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4.1 Introduction

This chapter explores the nutritional composition of insects and the potential benefits and drawbacks for their inclusion into animal feeds. There is increasing interest in the potential use of insects as novel ingredients in animal feeds, particularly for aquaculture, pets, poultry and pigs, while there is less interest in their use for ruminant diets. Insects are often thought of as a novel protein source to replace traditional protein sources such as soya bean meal and fishmeal (FM). However, there is scope for insects to be a high quality energy source as well.

This chapter will focus on the six species which are most commonly described for use in animal feed, namely black soldier fly (BSF; *Hermetia illucens*) larvae and prepupae, yellow mealworm (YM; *Tenebrio molitor*) larvae, superworm (SW; *Zophobas morio*) larvae, lesser mealworm (LM; *Alphitobius diaperinus)* larvae, house fly (HF; *Musca domestica*) larvae and house crickets (HC; *Acheta domesticus*).

Nutritional composition, variability observed due to manipulation of feed source, age, and developmental stage are compared, as well as evaluating their suitability for inclusion into animal feed.

4.2 Nutritional Composition

All six species of insect are rich in macro- and micronutrients and this, combined with the high concentrations of protein and oil, supports that whole unprocessed insect meal can be used as a complete feed source for animals. In all species, on a dry matter (DM) basis the main component is protein, followed by fat (Rumpold and Schlüter, 2013).

Table 4.1 describes the nutritional composition and range of values for the six species of insects compared to two traditional protein sources, namely hipro soya bean meal (HSBM) and FM. The general nutrient content is discussed in further detail below.

Table 4.1. Proximate nutritional composition of insect species. Main values are averages; values in brackets are the range

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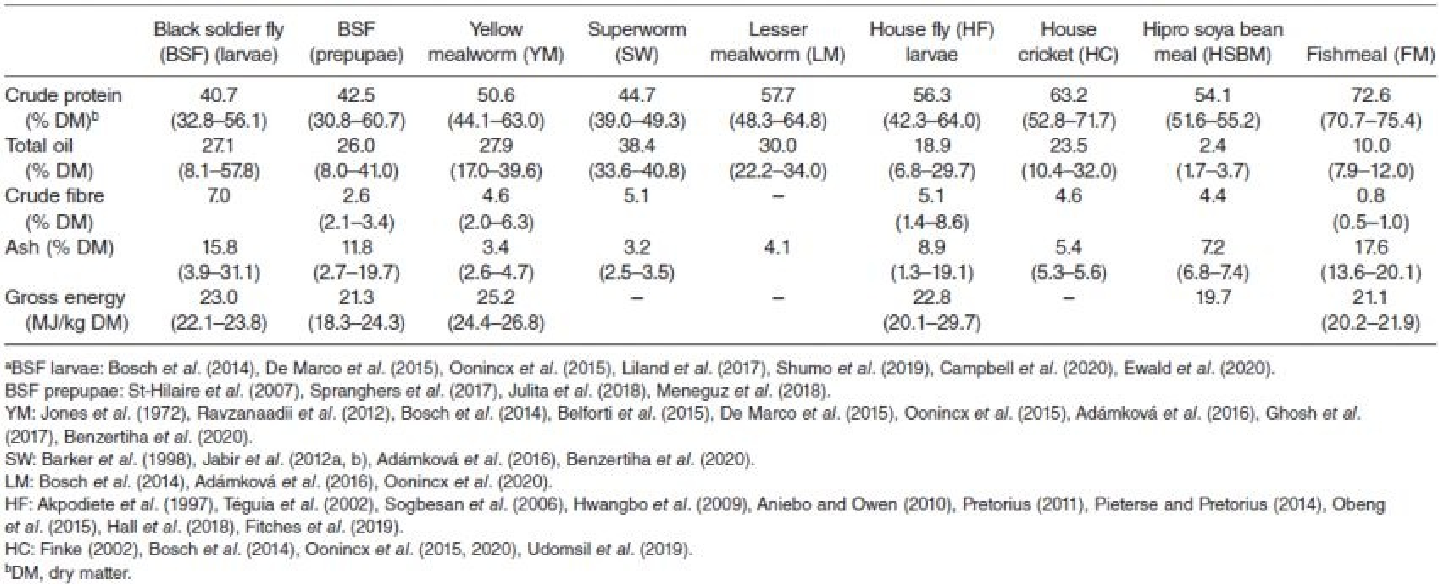
collected from literature.[a]



	Black soldier fly (BSF) (larvae)	BSF (prepupae)	Yellow mealworm (YM)	Superworm (SW)	Lesser mealworm (LM)	House fly (HF) larvae	House cricket (HC)	Hipro soya bean meal (HSBM)	Fishmeal (FM)
Crude protein (% DM)[b]	40.7 (32.8–56.1)	42.5 (30.8–60.7)	50.6 (44.1–63.0)	44.7 (39.0–49.3)	57.7 (48.3–64.8)	56.3 (42.3–64.0)	63.2 (52.8–71.7)	54.1 (51.6–55.2)	72.6 (70.7–75.4)
Total oil (% DM)	27.1 (8.1–57.8)	26.0 (8.0–41.0)	27.9 (17.0–39.6)	38.4 (33.6–40.8)	30.0 (22.2–34.0)	18.9 (6.8–29.7)	23.5 (10.4–32.0)	2.4 (1.7–3.7)	10.0 (7.9–12.0)
Crude fibre (% DM)	7.0	2.6 (2.1–3.4)	4.6 (2.0–6.3)	5.1	–	5.1 (1.4–8.6)	4.6	4.4	0.8 (0.5–1.0)
Ash (% DM)	15.8 (3.9–31.1)	11.8 (2.7–19.7)	3.4 (2.6–4.7)	3.2 (2.5–3.5)	4.1	8.9 (1.3–19.1)	5.4 (5.3–5.6)	7.2 (6.8–7.4)	17.6 (13.6–20.1)
Gross energy (MJ/kg DM)	23.0 (22.1–23.8)	21.3 (18.3–24.3)	25.2 (24.4–26.8)	–	–	22.8 (20.1–29.7)	–	19.7	21.1 (20.2–21.9)

[a] BSF larvae: Bosch *et al.* (2014), De Marco *et al.* (2015), Oonincx *et al.* (2015), Liland *et al.* (2017), Shumo *et al.* (2019), Campbell *et al.* (2020), Ewald *et al.* (2020).
BSF prepupae: St-Hilaire *et al.* (2007), Spranghers *et al.* (2017), Julita *et al.* (2018), Meneguz *et al.* (2018).
YM: Jones *et al.* (1972), Ravzanaadii *et al.* (2012), Bosch *et al.* (2014), Belforti *et al.* (2015), De Marco *et al.* (2015), Oonincx *et al.* (2015), Adámková *et al.* (2016), Ghosh *et al.* (2017), Benzertiha *et al.* (2020).
SW: Barker *et al.* (1998), Jabir *et al.* (2012a, b), Adámková *et al.* (2016), Benzertiha *et al.* (2020).
LM: Bosch *et al.* (2014), Adámková *et al.* (2016), Oonincx *et al.* (2020).
HF: Akpodiete *et al.* (1997), Téguia *et al.* (2002), Sogbesan *et al.* (2006), Hwangbo *et al.* (2009), Aniebo and Owen (2010), Pretorius (2011), Pieterse and Pretorius (2014), Obeng *et al.* (2015), Hall *et al.* (2018), Fitches *et al.* (2019).
HC: Finke (2002), Bosch *et al.* (2014), Oonincx *et al.* (2015, 2020), Udomsil *et al.* (2019).
[b] DM, dry matter.

Protein and amino acids

The crude protein content of the insects discussed in this chapter ranges from 41% to 63% DM (Table 4.1). These values compare well to HSBM at 54% and FM at 73% (Table 4.1). Based on these values insects in general would supply a suitable amount of crude protein for use in animal feeds. According to literature values (Table 4.1), the highest average protein value is in HC and lowest in BSF larvae. However, there is considerable variability in the data available, with individual studies suggesting the lowest protein value for BSF larvae is 33% DM (Shumo *et al.*, 2019), while the highest value for HC is 72% DM (Finke, 2002).

There are concerns that the crude protein content of insects is overestimated due to the insect cuticle (exoskeleton) (Jonas-Levi and Martinez, 2017). Crude protein is generally calculated by multiplying the total nitrogen content (from analysis) by a conversion factor of 6.25. However, as the insect cuticle contains the nitrogen-rich polysaccharide chitin, which comprises *N*-acetyl glucosamine monomer units (Rathore and Gupta, 2015), it has been suggested that this may lead to overestimation of the protein content. Furthermore, any protein in the cuticle, alongside chitin and fats, are bound in a matrix (Barker *et al.*, 1998), potentially reducing the bioavailable protein content further.

A recent study suggested that the protein content of insects should be quantified by first subtracting the nitrogen in the cuticle from the total nitrogen content (Jonas-Levi and Martinez, 2017). Two alternative nitrogen conversion factors of 4.76 and 5.60 have been proposed based on analysis of BSF, YM and LM (Janssen *et al.*, 2017). These authors suggested that the 4.76 conversion factor should be used to quantify the crude protein content of whole larvae/insects, while 5.60 should be used to quantify the crude protein content of protein extracts from those insects. Ewald *et al.* (2020) calculated the crude protein content of BSF larvae using both 6.25 and 4.76 conversion factors (multiplying nitrogen by these to estimate protein levels). On average, the use of the 6.25 conversion factor led to a 9% higher crude protein value across all feed sources. An additional factor to consider is that chitin content of insects varies with stage of development and species.

Crude protein content is often compared; however, there is no dietary requirement for protein per se. Dietary requirement is for essential amino acids (EAAs) and conditionally essential amino acids (CEAAs) being required in the feed at times to achieve maximum growth efficiency, for example for fast-growing young mammals or birds (McDonald *et al.*, 2011). For plant-based feed ingredients such as HSBM, the limiting EAAs (i.e. those below the animal's requirement) are often lysine and methionine. Protein quality relates to the EAA and CEAA content (measured in milligrams per gram of protein) combined with the amino acid digestibility or bioavailability. Hence it is important to consider these factors when considering any novel protein source for use in animal feeds.

Table 4.2 displays the amino acid composition of the main insect species. Those which are limiting for animal feed and pet food are sulfur-containing amino acids, methionine and cysteine (Table 4.2). For the EAAs, insects are generally comparable to HSBM and FM (Table 4.2). However, LM and BSF larvae and prepupae are higher in histidine than both HSBM and FM (Table 4.2).

Table 4.2. Amino acid composition (mg/g protein) of insect species. Values are averages from literature, with range in brackets below. From St-Hilaire *et al.*, 2007; Jabir *et al.*, 2012a, b; Makkar *et al.*, 2014; De Marco *et al.*, 2015; Zielinska *et al.*, 2015; Spranghers *et al.*, 2017; Biasato *et al.*, 2018; Hall *et al.*, 2018; Benzertiha *et al.*, 2020; Ritvanen *et al.*, 2020; Soetemans *et al.*, 2020.

	Black soldier fly (BSF) (larvae)	BSF (prepupae)	Yellow mealworm (YM)	Superworm (SW)	Lesser mealworm (LM)	House fly (HF) larvae	House cricket (HC)	Hipro soya bean meal (HSBM)	Fishmeal (FM)
Crude protein (% DM)[a]	36.9	42.0	51.0	49.3	41.3	57.9	52.8	55.2	74.8
Histidine (mg/g CP)[a]	30.6	31.0 (27.1–33.0)	27.8 (17.2–32.1)	21.2 (13.8–28.6)	41.3 (37.7–45.2)	29.1 (24.0–34.1)	23.0	27.0	23.8
Isoleucine (mg/g CP)	46.6	43.9 (41.7–46.6)	38.8 (26.6–44.3)	32.8 (21.4–44.2)	55.3 (45.6–64.3)	37.2 (32.0–42.5)	42.0	46.0	42.1
Leucine (mg/g CP)	65.0	70.3 (69.4–71.1)	64.6 (57.8–80.4)	51.2 (30.2–72.2)	88.7 (79.7–96.9)	63.0 (54.0–71.9)	75.0	77.0	71.8
Lysine (mg/g CP)	60.4	57.6 (53.4–60.9)	58.0 (38.4–68.5)	44.6 (34.3–55.0)	46.0 (4.8–83.0)	72.7 (61.0–84.3)	59.0	62.0	75.4
Valine (mg/g CP)	59.6	61.8 (58.5–65.4)	56.4 (47.0–70.9)	44.8 (29.4–60.2)	81.1 (56.5–93.9)	45.3 (40.0–50.6)	65.0	48.0	49.7
Methionine (mg/g CP)	24.5	18.3 (16.5–20.6)	17.5 (15.5–19.3)	9.7 (5.8–13.6)	12.1 (2.1–19.3)	25.8 (22.0–29.6)	18.0	14.0	25.7
Cysteine (mg/g CP)	37.4	5.5 (5.1–6.1)	17.8 (11.1–23.9)	5.4 (0.8–9.9)	4.2 (0.3–8.6)	19.8 (7–32.6)	9.0	16.0	8.4
Phenylalanine (mg/g CP)	39.0	48.7 (41.3–58.2)	33.7 (22.0–41.1)	29.4 (21.9–36.9)	53.1 (43.2–59.6)	58.5 (46.0–71.0)	39.0	51.0	38.9
Threonine (mg/g CP)	41.2	39.3 (37.6–40.8)	40.2 (35.3–53.4)	30.6 (21.2–36.9)	49.1 (37.1–57.1)	48.7 (35.0–62.3)	40.0	38.0	41.4
Tryptophan (mg/g CP)	–	14.5 (12.5–16.3)	10	12	–	46.0 (15.0–77.0)	8.0	14.0	10.3
Arginine (mg/g CP)	52.6	50.9 (46.2–60.8)	44.1 (25.6–53.4)	36.5 (21.9–51.1)	126.1 (95.2–158.8)	51.3 (46.0–56.6)	54.0	73.0	65.2
Proline (mg/g CP)	101.1	54.7 (52.4–58.2)	58.5 (43.4–66.6)	40.0 (25.7–54.4)	65.5 (43.7–75.9)	38.9 (33.0–44.7)	61.0	50.0	40.4
Glycine (mg/g CP)	51.8	55.0 (52.3–58.5)	43.5 (31.8–56.4)	37.5 (24.5–50.5)	60.1 (43.7–75.9)	47.7 (42.0–53.4)	57.0	42.0	62.4

[a] DM, dry matter; CP, crude protein.

For poultry, arginine is highlighted as an EAA as it is not supplied by metabolism (McDonald *et al.*, 2011). Many insects are lower in arginine, for example BSF larvae (52.6 mg/g CP (crude protein)) are lower compared to FM (65.2 mg/g CP) and HSBM (73 mg/g CP), but LM are higher (126.1 mg/g CP) (Table 4.2). Furthermore, proline and glycine are

CEAAs for poultry as they have limited ability to synthesize proline and growing chicks often require additional glycine to maximize production efficiency (McDonald *et al.*, 2011). Insects are a good source of these CEAAs, with the proline content of all the described species, except SW and HF, being higher than HSBM and FM (Table 4.2). Glycine content of the main species is comparable to HSBM but lacking as compared to FM (Table 4.2). As cats and other obligate carnivores are unable to synthesize taurine from cysteine (McDonald *et al.*, 2011), their feeds are supplemented to supply this. However, crickets have been highlighted to contain higher levels of taurine compared to other insect species (Finke, 2002), and could therefore potentially be used to provide this amino acid in pet food.

As with all compound feeds, any deficiencies should be avoided by combining with other protein sources or the addition of synthetic amino acids. However, this has cost implications and not all amino acids are commercially available or economically viable. For example, valine and tryptophan remain very expensive to include synthetically and so protein sources which are higher in these amino acids would be beneficial in least-cost formulations. From the six insect species, all apart from SW and HF have an increased valine content compared to HSBM (Table 4.2). With these elevated amino acid levels compared to plant protein sources, insects could be used as a cost-effective source.

Protein digestibility of insect meal has been suggested to be between 77% and 98% (Ramos-Elorduy *et al.*, 1997), although as with protein content there is variation between species. Apparent protein digestibility in broilers fed YM larval and BSF larval meal has been reported as 60% and 51%, respectively (De Marco *et al.*, 2015). *In vitro* studies, utilizing a monogastric model, have reported higher protein digestibilities at 65–69% for both YM and BSF larval meal (Marono *et al.*, 2016). Apparent and true ileal digestibility values were found to be similar between HF and FM in broilers (Hall *et al.*, 2018). In general, insect-derived amino acids are readily available with digestibility values comparable to or better than HBSM and FM. BSF larval meal has been highlighted to have a lower amino acid digestibility compared to other insect species (Finke and Oonincx, 2017). De Marco *et al.* (2015) also highlighted that the methionine in both BSF and YM larvae when fed to broilers had the lowest ileal digestibility compared to the other amino acids. As with all digestibility trials, the methods used to calculate the digestibility values have an impact on the results obtained, therefore limiting comparability between studies (Masey O'Neill *et al.*, 2014).

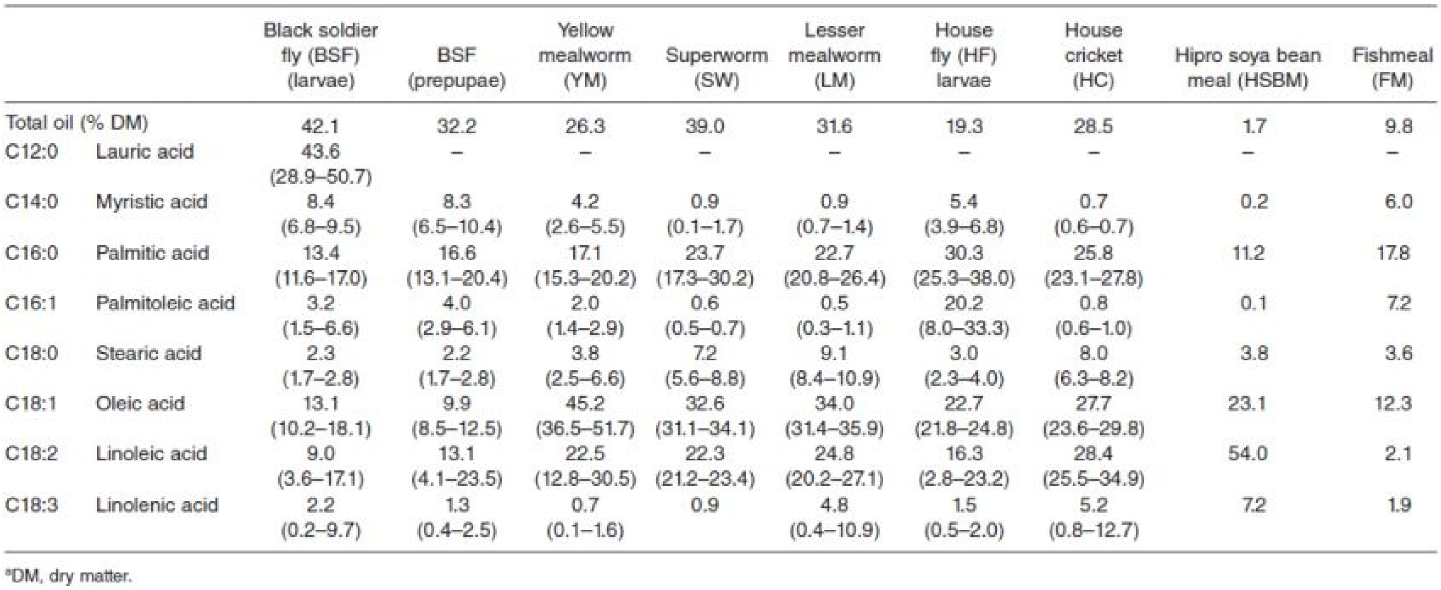
Another concern for feed ingredients is that protein digestibility can be reduced due to the presence of anti-nutritional factors such as trypsin inhibitors or protein binding molecules such as tannins, common to plant-based protein. Protein digestibility in insects has been reported to be negatively correlated to the chitin content (Marono *et al.*, 2016). Chitin could be acting as an anti-nutritional factor in insects, due to its ability to bind to both protein and amino acids (Rathore and Gupta, 2015), thereby decreasing digestibility and absorption in the animal gut. Insects which have a high chitin content (highly sclerotized), for example HC, are likely to have a lower protein digestibility compared to other larval species (Finke and Oonincx, 2017). Chitin has been shown to be beneficial at low inclusions and so this area warrants further investigation to understand at what level chitin becomes detrimental.

Oil and fatty acids

The oil content of the six insect species ranges from 19% to 38% DM (Table 4.1) being, on average, highest for SW and lowest for HF larvae. Clearly, when compared to fat-extracted protein sources such as HSBM at 2.4% and FM at 10%, insects contain considerably more fat. However, it is important to remember that both traditional protein sources have been highly processed to remove the fat which has economic value to human and industrial markets.

The fat content of insect meal is predominantly made up of triacylglycerol (Kourimska and Adámková, 2016). The individual fatty acids content is summarized in Table 4.3. Fatty acids are subdivided into saturated, monounsaturated (MUFA) and polyunsaturated (PUFA). The main fatty acids in insect meals are palmitic (C16:0), oleic (C18:1) and linoleic (n-6 C18:2) acids, respectively. Uniquely, BSF larvae also contain high levels of the medium-chain saturated fatty acid (MCFA), lauric acid (C12:0) (Table 4.3), at an average of 43.6% of the total fatty acids this is comparable to coconut oil (Dayrit, 2015). MCFA are known to have antibacterial properties, which could be utilized to improve gut health in piglets (Jackman *et al*., 2020). As can be seen, insect meal is intrinsically low in the omega-3 PUFA, alpha-linolenic acid (n-3 C18:3) and even when they are specifically fed on sources of this fatty acid there is little evidence that they can synthesize longer chain highly unsaturated PUFA, such as eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA). The requirements of these fatty acids for carnivorous marine fish (such as salmon) means that insect-containing feeds would still need to be supplemented with fish oil (or other sources of EPA and DHA such as algae).

Table 4.3. Total oil (% DM)[a] and fatty acid composition (% total fatty acids) of insect species. Values are averages from literature, with range in brackets below. From: Hwangbo *et al*., 2009; Jabir *et al*., 2012a, b; Ravzanaadii *et al*., 2012; Makkar *et al*., 2014; Pieterse and Pretorius, 2014; Oonincx *et al*., 2015; 2020; Zielinska *et al*., 2015; Adámková *et al*., 2016; Hussein *et al*., 2017; Meneguz *et al*., 2018; Cullere *et al*., 2019.



		Black soldier fly (BSF) (larvae)	BSF (prepupae)	Yellow mealworm (YM)	Superworm (SW)	Lesser mealworm (LM)	House fly (HF) larvae	House cricket (HC)	Hipro soya bean meal (HSBM)	Fishmeal (FM)
Total oil (% DM)		42.1	32.2	26.3	39.0	31.6	19.3	28.5	1.7	9.8
C12:0	Lauric acid	43.6 (28.9–50.7)	–	–	–	–	–	–	–	–
C14:0	Myristic acid	8.4 (6.8–9.5)	8.3 (6.5–10.4)	4.2 (2.6–5.5)	0.9 (0.1–1.7)	0.9 (0.7–1.4)	5.4 (3.9–6.8)	0.7 (0.6–0.7)	0.2	6.0
C16:0	Palmitic acid	13.4 (11.6–17.0)	16.6 (13.1–20.4)	17.1 (15.3–20.2)	23.7 (17.3–30.2)	22.7 (20.8–26.4)	30.3 (25.3–38.0)	25.8 (23.1–27.8)	11.2	17.8
C16:1	Palmitoleic acid	3.2 (1.5–6.6)	4.0 (2.9–6.1)	2.0 (1.4–2.9)	0.6 (0.5–0.7)	0.5 (0.3–1.1)	20.2 (8.0–33.3)	0.8 (0.6–1.0)	0.1	7.2
C18:0	Stearic acid	2.3 (1.7–2.8)	2.2 (1.7–2.8)	3.8 (2.5–6.6)	7.2 (5.6–8.8)	9.1 (8.4–10.9)	3.0 (2.3–4.0)	8.0 (6.3–8.2)	3.8	3.6
C18:1	Oleic acid	13.1 (10.2–18.1)	9.9 (8.5–12.5)	45.2 (36.5–51.7)	32.6 (31.1–34.1)	34.0 (31.4–35.9)	22.7 (21.8–24.8)	27.7 (23.6–29.8)	23.1	12.3
C18:2	Linoleic acid	9.0 (3.6–17.1)	13.1 (4.1–23.5)	22.5 (12.8–30.5)	22.3 (21.2–23.4)	24.8 (20.2–27.1)	16.3 (2.8–23.2)	28.4 (25.5–34.9)	54.0	2.1
C18:3	Linolenic acid	2.2 (0.2–9.7)	1.3 (0.4–2.5)	0.7 (0.1–1.6)	0.9	4.8 (0.4–10.9)	1.5 (0.5–2.0)	5.2 (0.8–12.7)	7.2	1.9

[a] DM, dry matter.

Fibre

The crude fibre (CF) content of the six insect species ranges from 3% to 7% DM (Table 4.1). The highest is observed in BSF larvae and the lowest in the BSF prepupae. The CF content of insects is mainly formed of insoluble chitin (van Huis *et al.*, 2013), and as such is very different to that of plant-based ingredients. However, chitin and its derivatives have been shown to have antioxidant and anti-inflammatory properties (Park and Kim, 2010), and could be used to stimulate the immune system or modulate animal gut health. Further research is needed to fully understand how best to apply chitin whether in whole insect meal or as a purified material.

In the literature there is more data reporting the fibre content of insects as CF compared to other analytical methods such as acid detergent fibre (ADF) and neutral detergent fibre (NDF). Though some data is available for BSF larvae with ADF ranging from 13% (Campbell *et al.*, 2020) to 29% (Shumo *et al.*, 2019) and NDF from 7.9% (Campbell *et al.*, 2020) to 15% (Shumo *et al.*, 2019), on a DM basis, compared to 14% NDF and 8.4% ADF for HBSM. When formulating, ADF and NDF are sometimes used, however, when labelling feed products, CF is still the main nutrient required for regulatory purposes.

Ash and minerals

The ash content of the six insect species ranges from 3% to 16% DM, being highest in BSF larvae and lowest in SW (Table 4.1). In general, the mineral levels are likely to meet the requirements of most animals (Barker *et al.*, 1998), although mineral bioavailability is not well described and may be reduced due to binding with chitin (Rathore and Gupta, 2015). The calcium content of insects is generally lower than other animal sources of protein such as FM due to the lack of a calcified skeleton (Finke and Oonincx, 2017). However, there are significant species differences, for instance, the calcium content of BSF larvae has been reported as 9340 mg/kg compared to 765 mg/kg in HF larvae (Finke, 2013). Similarly, the magnesium, manganese and iodine contents of BSF larvae were all higher than HF larvae (Finke, 2013). Phosphorus in plant-based feed ingredients is often in the form of phytate, which is not bioavailable in monogastric animals, whereas this is not the case for insects where the phosphorus is more bioavailable. This, therefore could be beneficial in diet formulations.

Overall, it appears that insect meal represents a potentially useful protein, fibre and mineral source. Depending on dietary requirements, extraction of fat may be needed. Further work is required to evaluate whether and at what levels chitin may be beneficial as a component of feed or whether its anti-nutritional effects mean that it should be removed. Insect meal may also, where formulated correctly, be a useful ingredient for balancing feed formulations to overcome some of the limitations of plant-based feed materials.

4.3 Variation in the Nutritional Composition of

Insects

As highlighted in Tables 4.1, 4.2 and 4.3 there is variation in the nutrient content of each species shown. There are two main drivers for the variation in nutritional composition.

The first is the type of feed that the insects are grown on. The nutritional composition of the feed is often reflected in the final nutritional composition of the insect. Literature-based data for feed sources do not necessarily reflect the growing commercial industry. From the studies compared in this chapter, the fat content appears to be the most variable, both in total amount and fatty acid composition. While this obviously influences the protein content (on a dry weight basis) there is little evidence for variation in amino acid composition within species when reared on different substrates (Fitches *et al*., 2019).

Insects produced on high carbohydrate-based feeds appear to accumulate more fat in comparison to other feeds. For example, BSF larvae fed on a bread-based feed with high carbohydrate levels accumulated more fat compared to a general food waste-based feed (Ewald *et al*., 2020). When raised on brewer's grains waste, HF larvae had a higher total fat content and lower total protein content than larvae raised on poultry waste (Obeng *et al*., 2015). Feeding 100% algae to BSF larvae resulted in a fat content of 8.1% compared to 22% when they were fed a 50% algae 50% processed wheat feed, whereas protein content remained similar (Liland *et al*., 2017). When fed just plant materials, YM had the highest protein content (Adámková *et al*., 2016), compared to other studies where YM were fed on other feed sources, including by-products. However, the developmental stage of the larval species is not reported so could differ between studies, partially causing the differing protein values. Fat content has been suggested to be primarily due to diet suitability whereas protein content is set by species and life stage (Fitches *et al*., 2019).

The greatest variation within species is found in ash content (Table 4.1). Feeding BSF larvae on a bread and mussel-based feed increased the ash content to 30% compared to 16% in those fed on food waste only (Ewald *et al*., 2020). However, this was likely due to the small fraction of feed present in the gut being included in the analysis (Ewald *et al*., 2020). This highlights the impact gut content can have on the nutritional value of whole insects and it is important to note that most published studies do not report whether the insect had undergone gut clearance.

BSF larvae, prepupae and HF larvae have been raised on a wide variety of feed substrates including animal waste-based feed. In general, other species tend to be fed plant-based waste materials. This highlights the opportunity to feed waste-based feeds and benefit from a more cost-effective production, although derived products must be evaluated for nutritional quality and to ensure any potential hazards have been mitigated before incorporation into the animal feed chain. There appears to be a lack of studies on the effects of different feed sources on the nutritional composition of crickets, possibly because much of this current market is for direct human consumption and has focused on rearing the insects on human edible ingredients, such as wheat.

The second driver for variation in nutritional composition is the growth or developmental stage of the insects, which is influenced by the type of insect and whether it is holometabolous (larval followed by a pupal stage and then the adult form; three distinct phenotypes) or hemimetabolous (larvae hatch into a form similar to the adult) (Finke and Oonincx, 2017). In general, there is a higher fat content of larval insect meals when compared to the adult form. This can be seen when comparing BSF larvae and BSF prepupae (Table 4.1). Fat content increases as larvae develop towards pupation, as this is the main energy source used for metamorphosis in holometabolous insects (Finkel, 1948). For example, 5-day-old BSF larvae had a fat content of 9.7% (Ewald *et al*., 2020) compared to 26% for prepupae on a DM basis (see Table 4.1).

4.4 Suitability for Inclusion into Compound Animal Feed

As discussed, the nutritional composition of insects has been reasonably well studied and appears to be suitable for inclusion into compound animal feeds.

In published feeding trials where insects have been included in animal feeds, the insects are normally in the form of a crushed whole insect meal which has been mixed into a crumb or mash-type feed. There is limited evidence of insects being incorporated into processed feeds such as pellets. Therefore, the processing and extrusion processes used to form a pellet or kibble may potentially affect the composition and digestibility of insect products. For example high temperatures could result in Maillard reactions (Kröncke *et al*., 2019) and therefore have an impact on the amino acid profile. This, however, is true for all proteins as most digestibility studies are run on unprocessed meal diets.

The presence of unsaturated fatty acids within the high fat content of whole insect meals increases the risk of oxidation and rancidity of the product (van Huis *et al*., 2013). As with FM there may be a need to include antioxidants during processing to maintain the product's shelf life both as a raw material and in the finished feed. The chitin content may also undergo unwanted changes which could increase binding to other nutrients and impact digestibility. Lastly, palatability and colour parameters have not been fully evaluated, and it is known that BSF and YM, for example, contain phenols which over time darken the colour of the insect meal (Janssen *et al*., 2019).

There are minimal negative factors with using insects as a feed ingredient in compound feed where formulation programmes are used, as most parameters for nutritional values are known. However, there is scope to improve data regarding the different fibre types and specific insect products. The chitin fraction of the insect material should be analysed or estimated and formulated for finished feeds to help ensure gut health aspects are captured and recommended levels are not exceeded.

The previous sections have focused on insects being used as a completely unprocessed insect meal. However, the high fat content could cause issues with processing into specific feed forms and would therefore impose a maximum insect product inclusion level into some diets, especially monogastric feeds. HSBM and FM are processed to remove most of the oil, leaving a high protein by-product with the oil available for human consumption and industrial uses. Soya and fish oils can be purchased to be added separately to compound feed where costs allow. The same process could be applied to insect meal creating two separate product streams, a high-protein insect meal and an insect oil. For example, Schiavone *et al.* (2017) produced highly defatted BSF meal, with a fat content of 4.6% DM, which brought the product much closer to the composition of HSBM. Furthermore, this defatted meal had a crude protein content of 66% DM (calculated using the 6.25 nitrogen conversion factor) which is in fact higher than HSBM. Even if calculated using the lower conversion factor of 5.6 this would equate to ~59% crude protein DM which is still significantly higher than HSBM.

Additional products that could be extracted from insects are antimicrobial peptides (AMPs) (Wu *et al.*, 2018), these have potential as zootechnical feed additives. Certain AMPs have been shown to be beneficial in eliminating viruses and protozoa and to be effective against bacteria and fungi (Wu *et al.*, 2018). The AMP cecropin, which can be extracted from insects (Wu *et al.*, 2018), improved immune status and reduced intestinal pathogens in weaned piglets (Wu *et al.*, 2012) and it has shown to help improve nutrient utilization in broilers (Wen and He, 2012). Therefore, the use of such products in commercial animal feed may help to reduce the reliance on antibiotics and could be a natural tool for the control of unwanted pathogens. Nevertheless, if AMPs are to be used as a technical feed additive, their effects need to be evaluated and potentially registered for use in formulated animal feeds.

Gut clearance prior to processing should be considered as any microbial load in the insect gut could be transferred into the animal. For example *Escherichia coli* has been shown to be transmitted by HFs into the digestive systems of cattle (Ahmad *et al.*, 2007). Effective management and processing should mitigate this, and heat treatment of insect meal should be used as a microbial decontamination step. Feed type also plays a role in this as there would be more risk associated with feeding insects on a manure-based feed in comparison to a cereal- or plant-based one. When YM are raised in an aseptic environment, they have been shown to have no bacteria or fungi in their gut (Genta *et al.*, 2006). Another concern is that certain insects have the potential to accumulate heavy metals (Belluco *et al.*, 2013). For example BSF produced on heavy metal-spiked feed accumulated cadmium (Diener *et al.*, 2015), but careful control of the insect feeding substrate would reduce this risk.

New high-density animal production systems such as commercial insect rearing could increase the risk and incidence of new emerging diseases and pathogens. While it has been suggested that these risks are fairly low (van Huis *et al.*, 2013) substrate monitoring, and appropriate processing, should ensure that insect products offer no greater threat as compared to other animal-based products for livestock and pet feeding.

Another potential drawback is allergenicity of insect-derived feed. Humans have been reported to develop such allergies and, in particular humans who are allergic to crustaceans have also been reported to be allergic to insects (van Broekhoven *et al.*, 2016). Literature seems scarce on the potential allergic response to feeding insects in animals, although as they are part of the natural diet of many birds, reptiles and fish this risk seems minimal. Some studies have shown no issues when feeding high levels (up to 70%) of HF larvae to broilers (Hall *et al.*, 2018). There may also be a need to mitigate against the danger that people working with insects could develop an allergic reaction (Jensen-Jarolim *et al.*, 2015). For example, if inclusion of insects into compound feed was done manually this would need to be managed through effective personal protective equipment (PPE) as it is for other feed materials and additives.

This chapter has highlighted that insect nutritional composition is influenced by feed source, species and stage of development. There is also increasing evidence that the nutritional composition of insects can be manipulated through using additives, hormones or genetic modification. These come with both positive and negative connotations. Additives such as those commonly used in animal feeding (minerals, enzymes, yeast and pre- or probiotics) may provide benefits for improved growth efficiency or improved nutrient composition which would have to be offset against the added cost.

As the study of insect rearing is still in its infancy, we can expect to see major improvements over the next few years. Insect growth regulators such as synthetic analogues of juvenile hormone are routinely used in pest control, but could be used to block metamorphosis of insects, thereby keeping insects in their larval form for longer (Jindra and Bittova, 2020). Genetic modification of insects is also possible using RNA interference (RNAi) technologies (Shelton *et al*., 2020) and CRISPR (clustered regularly interspaced short palindromic repeats) applications (Taning *et al*., 2017). However, both of these technologies are partially restricted by lack of full genomes for some species. By targeting specific genes that regulate body size and composition, it may be possible to improve nutritional composition or reduce variability to make insects even more suitable for inclusion into animal feeds. However, as the life cycle of insects is relatively short compared to other animal groups, natural selection is a potentially suitable method of manipulating growth and composition without the use of genetically modified material. Selecting for populations which grow faster on preferred feedstocks or which concentrate a specific nutrient from their feed may be beneficial for the supply chain.

4.5 Conclusion

Insects are a viable option as a novel feed ingredient, generally having a good nutritional profile and the potential for other added benefits. However, there is a need to standardize their production, feed source and developmental stage of the insect species to reduce compositional variability observed from the literature and to produce a safe, consistent product. There is also scope for the utilization of new processing technologies to further enhance the benefits of purified insect products for animal feeding.

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5 Closing the Loop with Industrial Insect Farming

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5.1 The Dawn of the Circular Economy and Industrial Insect Farming

According to the well-known Ellen McArthur Foundation, the circular economy is a societal economy model that has the objective to redefine growth, focusing on the wider and positive benefits of utilizing resources. It is the opposite of a linear economy, a model based on consumption of unrenewable resources – which has been the dominating system since the Industrial Revolution that started approximately three centuries ago. But the circular economy is not as such a completely new phenomenon; it has been present in society in various shapes during this time as a subsystem, particularly visible in, for example, recycling of raw materials over the last 50 years.

However, as a paradigm, the contemporary circular economy model is a new and conscious global concept that has not been paralleled since before the Agricultural Revolution some 10,000 years ago – where man was living in a hunter-gatherer society that required utilizing and reusing the scarce resources at hand intelligently. With growing evident global environmental and climatic problems caused by the linear economy and utilization of fossil fuels to produce energy, the dawn of the circular economy paradigm has become inevitable to obtain planetary balance. In this context, as well as driven by the United Nations Sustainable Development Goals (SDGs), insect farming has emerged as an industrial alternative to supporting resource-efficient production of feed, food and non-food products. Overall, industrial insect farming has the foundation to be incorporated in a circular economic model, but it does, like many other systems, have challenges that need to be overcome to ensure circularity, for example, in optimizing energy use as highlighted by Oonincx (Chapter 7, this volume).

5.2 Opportunities and Challenges of Utilizing Organic Wastes in an Industrial Setting

From a circular economic perspective, one of the greatest potential aspects of industrial

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insect farming could be the utilization of food waste. In the European Union (EU) alone, 88 million t of food is estimated to be lost annually, which is equivalent to an economic loss of > €140 billion (Stenmarck *et al.*, 2016; European Commission, 2017b). This societal opportunity is a top priority of the umbrella organization of the insect sector, the International Platform of Insects for Food and Feed (IPIFF), that focuses on utilizing waste from various categories, for example former foodstuff and catering waste as feed for insects as part of their current regulatory strategy. According to the recent position paper by IPIFF (2020) on the contribution of the European insect sector to improving sustainability from 'farm to fork', it is estimated that up to one-third of the food waste generated today could be suitable for industrial insect farming; before use in this way it would need to be declassified as 'waste'.

However, the application of insect products that are derived from production based on different food waste categories have different technical and regulatory potential regarding their end use. First, the classification of whether a certain substrate is waste or not has significant regulatory implications regarding whether it is legal to use as a feed material for farmed animals. Since 2017, seven species of insects, including black soldier fly (BSF; *Hermetia illucens*), yellow mealworm (YM; *Tenebrio molitor*) and house fly (HF; *Musca domestica*), have been defined as farmed animals by the European Commission (Commission Regulation (EU) 2017/893; European Commission, 2017a). Hence, the same legal requirements, with regards to general food law (Regulation (EC) 178/2002; European Commission, 2002) and feed hygiene (Regulation (EC) 183/2005; European Commission, 2005), apply for insects in order to comply with EU market regulations. For instance, this means, as stated in the feed marketing regulation (Regulation (EC) 767/2009; European Commission, 2009), that former foodstuffs containing meat and fish and catering waste are not, at present, legal to use as feed for insects. Moreover, animal manure such as pig slurry is likewise a 'no go'. While these legal restrictions primarily apply to the EU, it is possible to apply several different scenarios outside of Europe, including using catering waste, household waste and animal manure as feed for insects.

The EU regulatory framework has been constructed for vertebrates (fish, poultry, pigs and cattle), and insects are, as invertebrates, very different from the small group of animals that constitute and dominate current animal farming. Some of these differences are highlighted below and are likewise well described in recent publications (Surendra *et al.*, 2020) as well as in subsequent chapters of this book.

When it comes to feed safety some of the relevant species for industrial insect farming may also have biological competences that can overcome some of the regulatory barriers in the EU (and other regions) that have been implemented to secure the food production system. For instance, there is compelling evidence that BSF can help reduce levels of pathogenic microorganisms in the substrates used for rearing (Lalander *et al.*, 2013). This appears to be due to a high enzymatic activity in the larval gut as well as an intersectional difference in pH throughout the gut, ranging from approximately pH 2 to pH 8. Additionally, this is further supported by various defensive mechanisms including different antimicrobial peptides (AMPs) that help to control potentially harmful microorganisms (De Smet *et al.*, 2018; Gold *et al.*, 2018). Another risk that is normal if livestock manure is used as a substrate is the possible presence of veterinary pharmaceuticals (e.g. antibiotics) and antibiotic resistant bacteria. Here, BSF larvae have been found to promote the degradation of tetracycline (Cai *et al*., 2018). Moreover, other studies provide support of detoxification of other pollutants (Lalander *et al*., 2016) as well as degradation of certain mycotoxins (Bosch *et al*., 2017), while there is also evidence of bioaccumulation of certain metals (Proc *et al*., 2020). Other insect species, like HF (Nordentoft *et al*., 2017) and YM (Niermans *et al*., 2019), also appear to have similar biological competences that overall may be of great importance in future industrial insect farming with regards to supporting a circular economy with insects as a cornerstone in the food/feed production system.

5.3 Insects as Valorizers of Organic Wastes

It is one thing to be able to perform bio-sanitation and detoxification, but the organic wastes available as substrates for feeding to insects may not per se be eligible for industrial insect farming. Price and available volumes may, or may not, be an issue in this category of feed for insects. According to the organic waste used for insect feed, there may be a low output of insect biomass, or low product quality, due to the wastes' poor nutritional profile. Yet, this may potentially be buffered economically if an alternative business model of gaining revenue from collecting the organic waste is relevant. From a technical production perspective, there may be immense challenges due to large heterogenicity of the substrates used or too high variability within a specific substrate over the year.

To ensure a stable and well-performing insect production system, key parameters such as temperature in the substrate (which can be greatly affected by inherent microbiota), humidity, pH and nutritional value are pivotal and must be kept as stable as possible to ensure a 'smooth operation' that is predictable in output. Hence, it is important to design a set-up that provides the right conditions for scaling up industrial insect farming. For instance, regarding feed this means balancing the nutrients, dry matter and moisture level as well as eventually preconditioning the microbiota through fermentation.

A recent EU-funded study by the Danish Technological Institute (DTI), using various agro-residues as feed for BSF larvae, reports how testing a preselection of available substrates led to designing a composite feed that performed promisingly at pilot scale with a feed conversion rate of 2.5 (based on dry matter level) (Heckmann and Gligorescu, 2019). The DTI also tested pilot-scale production of BSF larvae using organic household waste (OHW) in a project supported by the Danish Environmental Protection Agency (Fischer *et al*., 2018). Initially, optimization of larval density, feed volume and feeding frequency was performed to ensure stable production at pilot scale. Subsequently, over a 1-year period (August 2016–September 2017) representing a full calendar cycle of OHW input, 25 pilot-scale batches were conducted using an average of *c*.58 kg OHW (wet weight)/batch. Although key production parameters had been standardized to a large extent, including keeping a stable production environment, there was still a considerable variation (at least from a commercial perspective) regarding the feed conversion ratio (FCR) of larvae fed with OHW. Overall, the macro-nutritional content of the OHW was relatively stable across batches, but the dry matter content fluctuated considerably. Thus, even though there was a good average FCR across batches of 2.8, it ranged from approximately 2 to 7 (based on dry matter content) (Fischer *et al*., 2018). This underscores the necessity of using a feeding substrate that ensures stable conditions for the larvae in providing a commercially relevant production system.

To capture the full circular economical potential of valorizing organic wastes into larval biomass with a homogenous content of protein, fat and chitin it is also obvious to focus on one of the major by-products of industrial insect farming, namely frass. Frass is, commonly speaking, insect manure and at industrial scale it constitutes a considerable amount of by-product that needs to be handled.

Overall, there are not a lot of studies on the application and benefits of frass yet, but evidence of increasing use of frass as biofertilizer in agriculture and horticulture is emerging (see Goubalan *et al*., Chapter 8, this volume) as well as application of frass in biogas production (Fischer *et al*., 2018). From an ecological and biological perspective, the former makes perfect sense as many insects, particularly in the juvenile life stage (larvae or nymphs), convert various fresh or decaying organic substrates into frass that is recycled back into the ecosystem as nutrients for plants (i.e. nature's approach to the circular economy). Hence, just like manure from vertebrate livestock such as poultry and pigs, there is an obvious potential for utilizing frass as biofertilizer.

It appears that the nutrients in the frass (such as N, P, K) are more readily bioavailable to plants as compared to mineral fertilizers. Moreover, like other animal manure, frass also replenishes organic matter and hence carbon to the soil (see review by Goubalan *et al*., Chapter 8, this volume for further details). Apart from these benefits, there is also another value of using frass. Compared to manure from poultry and pigs, for example, where ammonia may relatively easily evaporate into the atmosphere, frass is (generally) very dry and thus emits little smell – and therefore also reduces loss of nitrogen.

Overall, there appears to be some great environmental and economic benefits of utilizing frass in plant production that need further investigation to increase the understanding of the full potential of frass as a valuable by-product in industrial insect farming. Already several companies in the insect sector are marketing a commercial frass product.

5.4 Into the Future

Currently, IPIFF aims to get former foodstuffs containing meat and fish legalized as feed for insects and the European Commission appears to be aligned along those lines with the overarching 'Green Deal' (European Commission, 2019a) strategy and in particular the 'Farm to Fork' (European Commission, 2019b) initiative. Hence, there is hope in the EU for tapping into this large, underutilized resource in the foreseeable future which could support a production volume of several million tonnes of insects. There is optimism regarding the bio-sanitation potential of certain insect species but still a lot of evidence needs to be provided, not least at demonstration scale, prior to getting approval in the EU for using insects fed on organic wastes for applications such as in pet food or fish feed. Overall, there is great promise for industrial insect farming to unleash the circular economy in food/feed production (see Fig. 5.1).

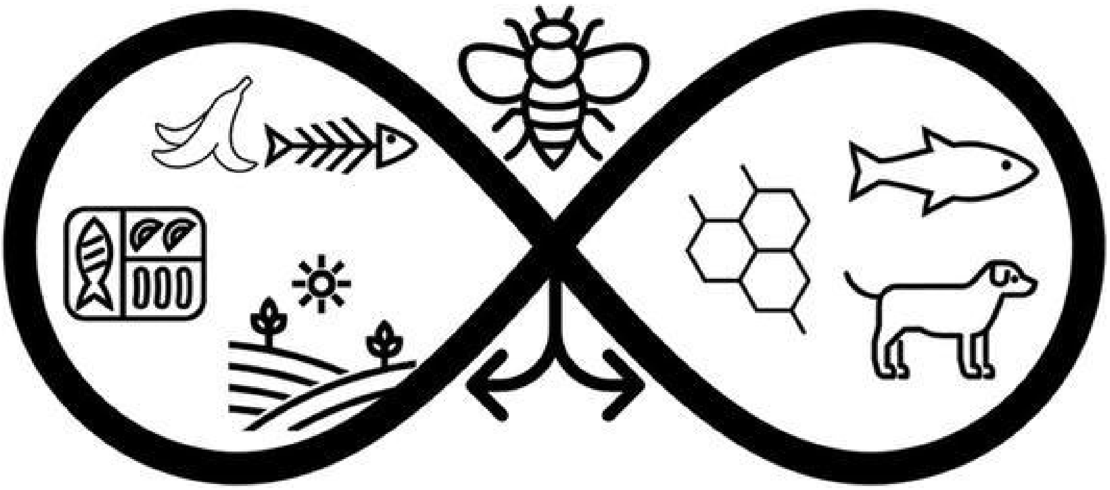

Fig. 5.1. The circular economy paradigm of insects. Conceptual overview of how insects can catalyse the food/feed production system converting organic wastes into high value products such as advanced molecules in technical applications or as pet food or feed.

Moreover, insects like BSF may reduce the volume, based on fresh matter, of their feed by > 85% during the bioconversion process (Fischer *et al*., 2018; Heckmann and Gligorescu, 2019); highlighting the potential to avoid transportation of large amounts of water present in the organic wastes. Hence, industrial insect farming should be considered in future planning of supply chain infrastructure aiming towards minimizing the distance between substrate and insect by identifying ‘back-to-back’ solutions, where substrate from one company is pumped directly into the neighbouring industrial insect farming facility. This is, for instance, the case for French Tereos and InnovaFeed that are creating this industrial symbiosis (Food Ingredients First, 2018).

Still, there are several different challenges in industrial insect farming that need to be overcome prior to unleashing the full potential of this novel approach to producing feed and food. Upscaling of production, development and amendment of relevant legislation, as well as consumer acceptance, are three of the major challenges of the insect sector, albeit the latter may not be a major issue when insects are applied as feed, it should not be dismissed when organic wastes are used as feeding substrate. The greatest challenge is by far upscaling, which involves understanding the biology of the specific insect species regarding nutrition, physiology, reproduction, genetics, (gut) microbiology and health, to mention some. There are likewise technical and economic challenges regarding automation and climate systems to support insect farming at industrial scale. The investment and running costs of these systems can be very high if they are not designed optimally.

It is hard to ‘get it right’ in the first generation of industrial insect farming; consider for instance the technical improvements that have been made in other livestock farming over the last few decades. Nevertheless, the insect sector needs to focus on closing the biggest gaps and concurrently ensure that industrial insect farming develops in a sustainable manner enabling zero or negative carbon footprints in the near future. There is a considerable opportunity in optimizing the climate system as shown by a recent Life Cycle Assessment

(LCA) study on the BSF production of Dutch Protix: revealing that 33% of the total energy consumption is used solely for the climate system (Smetana *et al.*, 2019). In this regard, it is also important to highlight that there is a need for the standardization of LCA to enable transparent comparison across different production types as outlined under the recent Product Environmental Footprint Category Rules (PEFCR) approach by the EU (European Commission, 2018).

As indicated above there may be an advantage of locating industrial insect farming near sources of organic wastes to optimize supply chain efficiency and strengthen the overall business model through industrial symbiosis. Yet, there are also other approaches that can generate future robust systems for producing feed and food. At large agricultural sites it may be possible to implement co-production between different on-farm activities – an approach that is already in operation in modern agriculture. In the future, insects produced on local residues and subsequently used on farm for poultry or pig production, for example, could, in combination with on-farm crop and biogas production, catalyse a local agro-symbiosis, hence closing the loop with industrial insect farming.

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6

Insect Farming: the Missing Link in the Circular Economy

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6.1 Introduction

By 2050, the global population will exceed 9.5 billion, requiring another *c*.60 million tonnes (t) of protein (Henchion *et al.*, 2017), with economic development pushing diets towards increasing levels of resource and emissions intensive animal-based proteins (Shepon *et al.*, 2018). However, terrestrial food production already accounts for 51% of the habitable surface, and of that 77% is used to grow feeds or graze animals, but only accounts for 18% of the world's calorie supply, and 37% of total protein (Richie, 2019), while agriculture accounts for 26% of global emissions and the livestock (including feeds) contribute more than 14.5% (Grossi *et al.*, 2019). Clearly, resource constraints including both feeds and foods are likely to limit supply chains in the short to medium term (Islam and Winkel, 2017).

At the same time, 822 million people are food insecure, with 25% of populations in developing countries undernourished, with progress since 2000 in addressing these problems faltering (Meneguz *et al.*, 2018). The United Nations estimates more than 1.4 billion t of food, with around 33% of the total food production wasted (Poore and Nemecek, 2018). The land required to produce this food is equivalent to approximately 14 million km^2, including 250 km^3 water, along with the energy and effort it takes to produce, process and transport it (van den Bos Verma *et al.*, 2020). Although it's worth noting some studies suggest these figures are significantly underestimated, food waste accounts for around 3.3 billion t carbon dioxide (CO_2) or 26–30% of global emissions (Global Hunger Index, 2019).

Climate change is also a critical factor as temperatures are predicted to increase by a minimum of 1.5°C in the coming decades with temperature fluctuations, increasing atmospheric CO_2, and changing seasonality adding pressure on ecosystems and biodiversity (Bastin *et al.*, 2019). These factors will have a significant effect across all aspects of primary production including changes in production capacity and crop quality, animal growth and milk production, water availability, animal health including pests and disease, reproductive capacity and biodiversity (Thornton *et al.*, 2009; Nardone *et al.*, 2010; Reynolds *et al.*, 2010; Chapman *et al.*, 2012; Henry *et al.*, 2012).

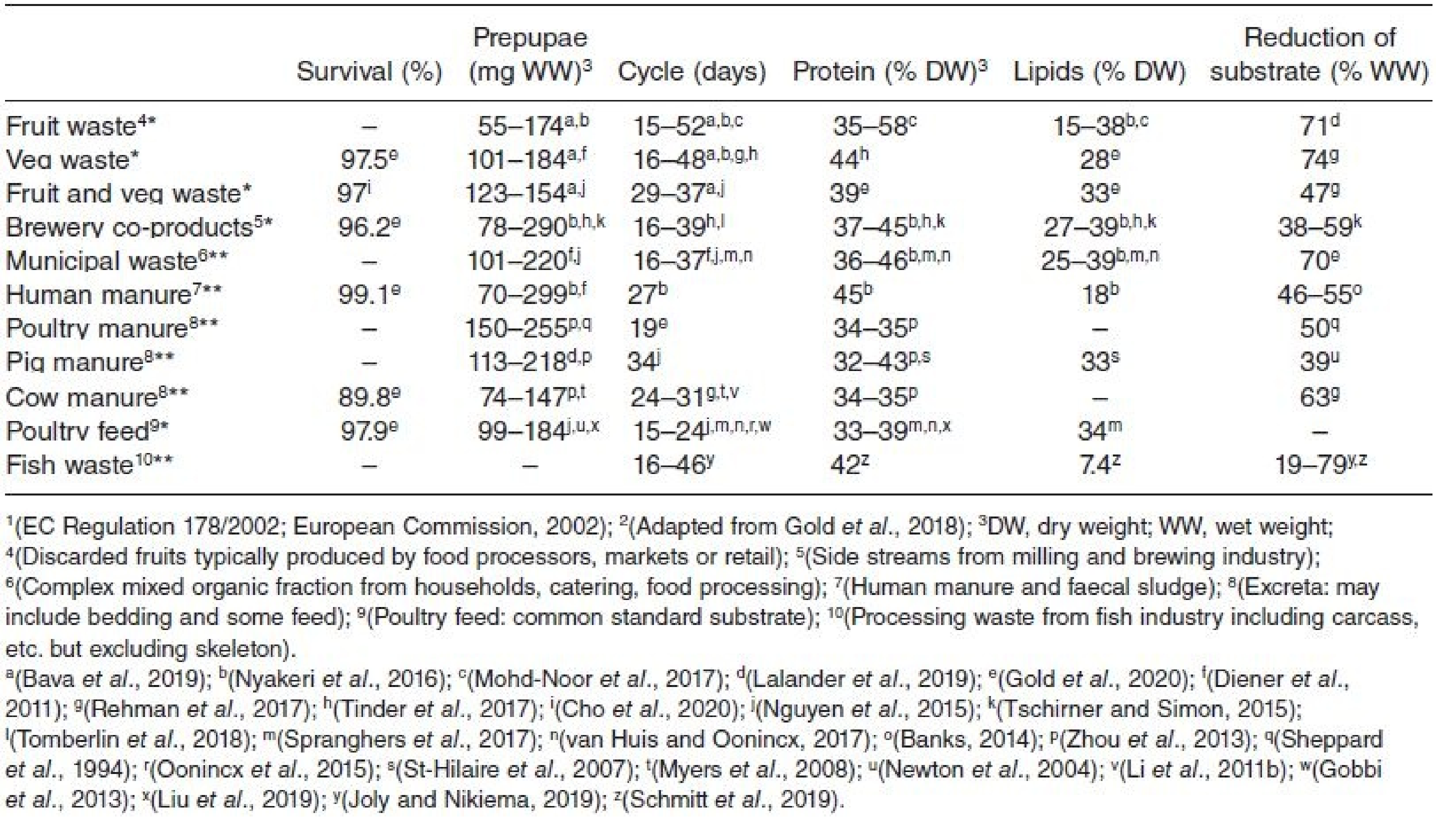
Fisheries and aquaculture will also be affected as species are temperature sensitive and wild stocks, needed to provide nutrient-dense foods for humans plus feeds for high value aquaculture and livestock (poultry and pigs), are already under pressure (Garcia and Rosenberg, 2010). As these sectors collectively supply approximately 17% of the global animal protein budget, almost 100% of the global omega-3 fatty acid supply, and employs more than 59 million people worldwide, future food, nutrient and economic security is uncertain (Hua *et al*., 2019). Moreover, because global aquaculture only generates *c*.0.47% of anthropogenic emissions, it presents an opportunity to provide nutrition at a very low greenhouse gas footprint (MacLeod *et al*., 2020).

6.2 The Circular Economy and Bioeconomy

One solution to this global issue is the circular economy (CE) where products and services are designed so that ‘wastes’ are recycled into useful forms which displace consumption of finite natural resources and minimize environmental footprints. For some materials, such as aluminium cans or glass, the recycling process and associated economic and environmental benefits are clear (Ozer *et al*., 2015). However, organic waste cycling is often overlooked due to low value compared to other waste materials (Joly and Nikiema, 2019; Teigiserova *et al*., 2019). Considering again food production, food waste holds the key to the solution, by utilizing the principles of the circular bioeconomy (CB). Because the system makes use of integrated multifunctional productive systems based upon cascading nested natural interactive cycles, the CB can provide not only the same benefits as the CE but also additional ones. While accounting for the described variability and effectively upcycling food waste to animal feeds and other products, the CB addresses many of the issues outlined earlier, in addition to supporting and enhancing the regeneration of natural systems.

With the focus on developing ‘alternative proteins’, insect farming has gathered interest as a research topic, as well as a business opportunity, resulting in industry growth acceleration in recent years. As natural detritivores and herbivores, insects can thrive on a range of organic substrates as food sources. Where insects are mass reared under controlled conditions, they can process significant volumes of food waste and other organic materials to produce multiple high value products and marketable commodities, as well as nutrient-dense biomass for utilization in feeds and foods (Table 6.1).

Table 6.1. Comparison of selected performance parameters for black soldier fly larvae fed on a range of permitted (*) and non-permitted (**) substrates[1] normalized to 60–70% moisture.[2]



	Survival (%)	Prepupae (mg WW)[3]	Cycle (days)	Protein (% DW)[3]	Lipids (% DW)	Reduction of substrate (% WW)
Fruit waste[4*]	–	55–174[a,b]	15–52[a,b,c]	35–58[c]	15–38[b,c]	71[d]
Veg waste[*]	97.5[e]	101–184[a,f]	16–48[a,b,g,h]	44[h]	28[e]	74[g]
Fruit and veg waste[*]	97[i]	123–154[a,j]	29–37[a,j]	39[e]	33[e]	47[g]
Brewery co-products[5*]	96.2[e]	78–290[b,h,k]	16–39[h,l]	37–45[b,h,k]	27–39[b,h,k]	38–59[k]
Municipal waste[6**]	–	101–220[f,j]	16–37[f,j,m,n]	36–46[b,m,n]	25–39[b,m,n]	70[e]
Human manure[7**]	99.1[e]	70–299[b,f]	27[b]	45[b]	18[b]	46–55[o]
Poultry manure[8**]	–	150–255[p,q]	19[e]	34–35[p]	–	50[q]
Pig manure[8**]	–	113–218[d,p]	34[j]	32–43[p,s]	33[s]	39[u]
Cow manure[8**]	89.8[e]	74–147[p,t]	24–31[g,t,v]	34–35[p]	–	63[g]
Poultry feed[9*]	97.9[e]	99–184[j,u,x]	15–24[j,m,n,r,w]	33–39[m,n,x]	34[m]	–
Fish waste[10**]	–	–	16–46[y]	42[z]	7.4[z]	19–79[y,z]

[1](EC Regulation 178/2002; European Commission, 2002); [2](Adapted from Gold *et al.*, 2018); [3]DW, dry weight; WW, wet weight; [4](Discarded fruits typically produced by food processors, markets or retail); [5](Side streams from milling and brewing industry); [6](Complex mixed organic fraction from households, catering, food processing); [7](Human manure and faecal sludge); [8](Excreta: may include bedding and some feed); [9](Poultry feed: common standard substrate); [10](Processing waste from fish industry including carcass, etc. but excluding skeleton).

[a](Bava *et al.*, 2019); [b](Nyakeri *et al.*, 2016); [c](Mohd-Noor *et al.*, 2017); [d](Lalander *et al.*, 2019); [e](Gold *et al.*, 2020); [f](Diener *et al.*, 2011); [g](Rehman *et al.*, 2017); [h](Tinder *et al.*, 2017); [i](Cho *et al.*, 2020); [j](Nguyen *et al.*, 2015); [k](Tschirner and Simon, 2015); [l](Tomberlin *et al.*, 2018); [m](Spranghers *et al.*, 2017); [n](van Huis and Oonincx, 2017); [o](Banks, 2014); [p](Zhou *et al.*, 2013); [q](Sheppard *et al.*, 1994); [r](Oonincx *et al.*, 2015); [s](St-Hilaire *et al.*, 2007); [t](Myers *et al.*, 2008); [u](Newton *et al.*, 2004); [v](Li *et al.*, 2011b); [w](Gobbi *et al.*, 2013); [x](Liu *et al.*, 2019); [y](Joly and Nikiema, 2019); [z](Schmitt *et al.*, 2019).

Although black soldier fly larvae (BSFL) performance fluctuates across and within substrates as a function of variation in processes, it is clear bioconversion is effective. Survival rates, waste volume reduction of up to 74% (wet weight (WW)) in as little as 15 days, and resultant biomass demonstrates 32–58% crude protein (dry matter (DM)) and 15–39% lipids (DM). BSFL processing supports an estimated reduction in the pollution potential of organic wastes by 60–70% (Newton *et al.*, 2005; van Huis and Oonincx, 2017). In combination with comparable amino acid profile to traditional feed ingredients including both soya and fishmeal, digestibility in excess of 70% (Liu *et al.*, 2019), along with favourable feeding trials (Zarantoniello *et al.*, 2019), there is growing interest in BSFL as a sustainable feed ingredient for fish, poultry, swine and pets.

It is of note that regulations restrict application of complex mixed or municipal food wastes and manures as substrates for feed ingredients within the EU and the UK, but the regulations vary globally (Table 6.2) (Caruso *et al.*, 2013; Čičková *et al.*, 2015; Joly, 2018; Joly and Nikiema, 2019; Tomberlin *et al.*, 2018).

Table 6.2. Comparison of geographic variation in regulations pertaining to use of processed insect protein in feeds.

Country/region	Summary
EU	Seven permitted species classed as farm animals and subject to same welfare and feed regulations. Recently approved for use in aquafeeds but substrates are restricted to pre-consumer organic wastes. Not permitted for use in livestock feeds
USA	Approved for use in fish and poultry feeds. Regulations vary by state with some allowing manures as feed
Canada	Approved for use in broiler feeds and up to 10% inclusion rate in salmon feeds
Australia	Insects fed with traceable substrates of vegetal and/or animal origin but excluding manures and municipal waste streams are permitted for use in poultry, swine and fish feeds

Developing countries	Use of insect protein to feed animals is often encouraged with little or no regulations and few legal barriers

Although the acceptability of some substrates may be questionable in food systems, it is still of value to understand the full potential of bioconversion. In addition to protein, oil from BSFL has been substituted for oil fractions in feed formulations for various fish species, poultry and pigs with no evidence of reduction in productive performance, carcass traits, or overall meat quality (Sealey *et al*., 2011; Okah and Onwujiariri, 2012; Li *et al*., 2016; Cullere *et al*., 2019). Moreover, BSFL oils are compliant with Fuel Standards for transport in the EU (Rutz and Janssen, 2006) and compares favourably with rapeseed oil biodiesel (Li *et al*., 2011a). Although some materials are currently out of scope within the EU (Table 6.1), were biodiesel the primary product rather than protein, and under comparison with typical energy resource plants, BSFL has the advantages of high productivity, a short life cycle, minimal resource use, and potential revalorization of surplus organic materials (Gao *et al*., 2019). Hence, a regulatory distinction for BSFL such as the UK T26 Vermicomposting Waste Exemption for treatment of kitchen waste in a wormery (The Environment Agency, 2014) could enable a paradigm shift in organic waste management.

After harvesting, the residue made up of spent feedstock, insect dejectate (frass) and a proportion of exoskeletons from moulting, is also valuable (Kagata and Ohgushi, 2012). Notwithstanding numerous studies which support increased economic and environmental sustainability in nutrient supply chains through integration of organic waste management (Chen *et al*., 2016; Mason, 2016; Payne *et al*., 2016; Zahn and Quilliam, 2017; Quilliam *et al*., 2020, etc.), industrial application in an agricultural context is still in its infancy. Several studies have also indicated BSFL can be induced to produce antimicrobial peptides of interest (Park *et al*., 2014; Spranghers *et al*., 2018; Vogel *et al*., 2018), and chitin from exoskeletons has a range of high value applications across textiles, papermaking, bioplastics, agriculture, forestry, food, medicine, bioengineering and water treatment (Aranaz *et al*., 2012; Fernando *et al*., 2016; Waśko *et al*., 2016; Gao *et al*., 2019; Kawasaki *et al*., 2019; Tharanathan and Kittur, 2003).

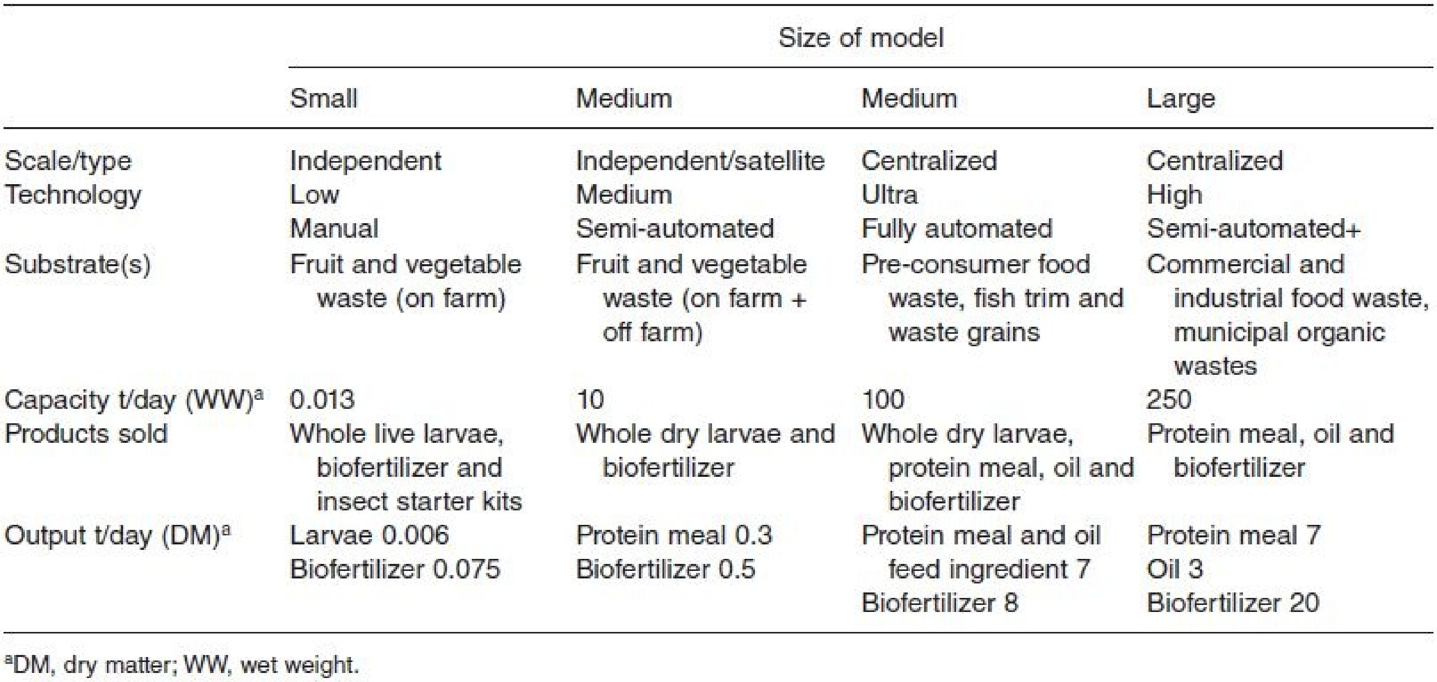
Clearly, insect bioconversion is very closely aligned with the principles of a CE producing a range of high value products, with the platform also offering a range of benefits over traditional waste management methods (Gold *et al*., 2020). However, there are still questions around optimal models for implementation.

6.3 Models of Implementation

Substrate type and availability is critical as it determines scale and distribution. Using Scotland as an example, almost 1 million t of vegetable field residues, 740 thousand t of commercial and industrial food waste, more than 600 thousand t of consumer food waste and almost 6 million t of agricultural slurries are generated every year (Zero Waste Scotland, 2019a). More specifically, 53.7 thousand t of brewers wastes, 4.4 million t of whisky co-products, and 189 thousand t of fish and shellfish residues are available (Zero Waste Scotland, 2015). It has been estimated that these waste streams could realize in excess of £800 million in value if fully utilized (Zero Waste Scotland, 2017).

However, although these materials are mapped to the regional level (Zero Waste Scotland, 2017), the data does not take seasonal variation, technical potential, substrate quality or availability into account. From this, considering just how diverse geographically and technically substrate source businesses can be, together with associated logistical issues, there is scope for a number of businesses and models (Table 6.3).

Table 6.3. 'Typical' black soldier fly larvae bioconversion business models. Adapted from Joly and Nikiema, 2019.



	Size of model			
	Small	Medium	Medium	Large
Scale/type	Independent	Independent/satellite	Centralized	Centralized
Technology	Low Manual	Medium Semi-automated	Ultra Fully automated	High Semi-automated+
Substrate(s)	Fruit and vegetable waste (on farm)	Fruit and vegetable waste (on farm + off farm)	Pre-consumer food waste, fish trim and waste grains	Commercial and industrial food waste, municipal organic wastes
Capacity t/day (WW)[a]	0.013	10	100	250
Products sold	Whole live larvae, biofertilizer and insect starter kits	Whole dry larvae and biofertilizer	Whole dry larvae, protein meal, oil and biofertilizer	Protein meal, oil and biofertilizer
Output t/day (DM)[a]	Larvae 0.006 Biofertilizer 0.075	Protein meal 0.3 Biofertilizer 0.5	Protein meal and oil feed ingredient 7 Biofertilizer 8	Protein meal 7 Oil 3 Biofertilizer 20

[a] DM, dry matter; WW, wet weight.

Given the volumes of available organic material, there is clearly room for both medium and large centralized facilities co-located with concentrated food production centres, delivering economy of scale, and potentially accessing additional value streams through technologies and infrastructure. At the other end of the scale, small independent sites could be on-farm valorization solutions through BSFL for poultry live feeding with reduced fertilizer costs. One model which is worth highlighting is a mixed model comprising centralized plus satellite facilities as proposed by Diener *et al.* (2015). Such a model could work at lower volumes and technology levels to capture wastes closer to source and take advantage of the larvae to reduce volume, recover value and concentrate nutrition.

For example, the Netherlands have implemented this semi-centralized model to diversify income streams for low margin farmers as part of the SUS-CHAIN project. Yellow mealworm (*Tenebrio molitor*) larvae are farmed across a cooperative of farms, which are harvested then shipped live to a centralized facility for processing. The cooperative can generate commercially relevant volumes of insects, use the residual frass as a biofertilizer, and avoid the additional regulatory and licensing complexity associated with becoming a feed business operator after further processing (Zero Waste Scotland, 2019b). Remembering that BSFL is potentially a global solution, and organic wastes are a universal product of humans, BSFL facilities have the potential to improve organic waste management, optimize environmental performance across food and drink supply chains, and create livelihood opportunities in all types and scale of economies.

6.4 Conclusions

In conclusion, it is not just that insect farming lends itself to CE/CB applications, it is central to it. Nature designed and perfected these natural, regenerative and restorative solutions over millions of years. To quote David Attenborough, ‘There are more than 4 million species of plants and animals on earth, that’s more than 4 million solutions to the problem of staying alive’ (David Attenborough cited in Shepherd, 2017).

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7 Environmental Impact of Insect Rearing

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7.1 Introduction

One of the first publications on using insects as feed came out approximately a century ago (Lindner, 1919). Scarcity of fats at the end of the First World War caused interest in alternative sources. In the aforementioned publication several species that are currently still investigated received attention, including yellow mealworms (YM; *Tenebrio molitor*) and common house fly (HF; *Musca domestica*). The primary idea was to convert underused resources towards useful compounds via insects. Whereas a shortage of fat was the concern at that time, nowadays protein scarcity drives the more recent investigations towards using insects as bio-converters and protein concentrators. Commercially-farmed insects have been perceived as sustainable alternatives to conventional animal products for quite some time (Oonincx, 2015). However, studies aiming to quantify their environmental impact have only become available during the last decade. This chapter provides a general overview of the currently available studies.

After this introductory paragraph, first, direct greenhouse gas (GHG) emissions from insects used as feed or food are discussed. Subsequently, data from life cycle assessments (LCAs) on commercially farmed insects are discussed per species. This is followed by a paragraph on the relevance of the utilized feed on the environmental impact of insects and their derived products, including suggestions to lower this impact. Then, the limitations in the available data are highlighted followed by a concluding paragraph, where the most relevant conclusions of this chapter are summarized.

7.2 GHG Emissions

GHG emissions, as a driver of climate change, have received ample attention in recent years. There are various GHGs differing in their potency (global warming potential) which is expressed as CO_2 equivalents, with CO_2 being used as the benchmark. Two of the other well-known GHGs are methane and nitrous oxide which are produced by bacteria and considered to be ~21 and ~310 times, respectively, more potent than CO_2 (Krey *et al.*, 2014; Buendia *et al.*, 2019).

Several insect groups, including cockroaches, termites and certain beetles have methane-producing bacteria in their gut (Hackstein and Stumm, 1994). The amount of methane produced in these species varies: sun beetle (*Pachnoda marginata*) larvae emit 4.9 g of methane/kg gain, whereas this is 1.4 g/kg for the Argentinean cockroach (*Blaptica dubia*) and only 0.1 g/kg for larvae of YM (Oonincx *et al.*, 2010). While methane production is environmentally disadvantageous, these bacteria (e.g. *Blattabacterium* sp.) can facilitate highly efficient use of dietary protein by converting uric acid to amino acids (Sabree *et al.*, 2009; Oonincx *et al.*, 2015).

Nitrous oxide emissions seem primarily associated with bacterial digestion of dead insects, rather than insect rearing per se (Oonincx *et al.*, 2010). Indeed, nitrous oxide emissions reported for house crickets in the latter study were associated with high cricket mortality, whereas a Thai study without high mortality deemed the nitrous oxide emissions negligible (Halloran *et al.*, 2017). In moist rearing substrates, such as those used for black soldier flies (BSF; *Hermetia illucens*) and HF, bacteria and fungi present in the substrate can contribute to direct GHG emissions. These contributions can be large: 34% of the emitted CO_2 in a BSF system and up to 92.5% for sun beetle larvae (Oonincx *et al.*, 2010; Parodi *et al.*, 2020). The latter value is probably an overestimate due to fungal development in substrate without larvae, whereas larval presence greatly reduces fungal development. Nitrous oxide emissions might well be associated with the feeding of decaying materials, rather than being associated with insect metabolism (Mertenat *et al.*, 2019). Even though only a few insect species have been studied, the methane and nitrous oxide emissions of farmed insects generally seem far lower than for conventional livestock (Oonincx *et al.*, 2010; Parodi *et al.*, 2020). The contribution of direct GHG emissions to the total emissions of insect farming systems is low when considered for the YM (0.3%), but higher for BSF (10–15%) (Oonincx and de Boer, 2012; Mertenat *et al.*, 2019; Parodi *et al.*, 2020).

7.3 Life Cycle Assessment (LCA) Methodology

LCA is a method that enables the comparison of environmental, social or economic impacts of similar products or services. It starts with defining the system border: the boundary of a production system (Oonincx and de Boer, 2012). This can include all system inputs and end at the farm gate (‘cradle to farm gate’). Alternatively, some inputs can be excluded, or the system can be extended to include post-farm processing.

Then, the indicators to be quantified are chosen. In environmental LCAs this can include GHG emissions, which fall under the indicator global warming potential (GWP). Other commonly used indicators are energy use (EU) as a measure of fossil fuel depletion, and land use to quantify the amount of arable land used in the production chain. Associated land use changes (LUC) can lead to deforestation, and thereby to GHG emissions, which are often mentioned separately. Other commonly used indicators are water depletion, effects on fresh and marine waters, acidification, and many more (Halloran *et al.*, 2017).

The environmental impact is subsequently coupled to a functional unit (FU), a quantitative measure indicating the function of a product and this is often expressed based on weight. For insects, commonly used FUs are kilograms of fresh weight, kilograms of protein, or kilograms of edible protein (Oonincx and de Boer, 2012). The environmental impact arising at different steps within the system border is then summed up, resulting in the total impact for a certain environmental indicator. Lastly, this is divided by the number of FUs and gives the environmental impact per FU. This value can then be used to compare the environmental impact between products with a similar function.

Production systems sometimes yield more than one product. For instance, when producing beer, the spent grains are considered a by-product. In such cases part of the environmental impact is allocated to the by-product based on relative weight, or on relative economic value.

At the time of writing the following insect species have been evaluated in an environmental LCA:

- YM (Oonincx and de Boer, 2012; Miglietta *et al.*, 2015; Thévenot *et al.*, 2018)
- superworms (SW; *Zophobas morio*) (Oonincx and de Boer, 2012);
- house crickets (HC; *Acheta domesticus*) (Halloran *et al.*, 2017);
- banded crickets (BC; *Gryllodes sigillatus*) (Suckling *et al.*, 2020);
- two-spotted crickets (*Gryllus bimaculatus*) (Halloran *et al.*, 2017; Suckling *et al.*, 2020);
- BSF (Salomone *et al.*, 2017; Mertenat *et al.*, 2019; Smetana *et al.*, 2019); and
- HF (van Zanten *et al.*, 2015).

Mealworm LCAs

The YM, together with the SW, were part of the first LCA on edible insects (Oonincx and de Boer, 2012). A farm, producing 83 t/year, was assessed from cradle to farm gate excluding buildings and equipment. Both fresh weight and weight of edible protein were used as FUs. Per kilogram of fresh weight, the GWP for these mealworms was 2.65 kg CO_2-eq., the EU amounted to 33.68 MJ and land use was quantified at 3.56 m^2. Feed production and transportation were the main drivers for GWP (56%), EU (43%) and land use (99%). These mealworms were considered an alternative form of animal protein for human consumption, and were therefore compared to milk, pork, chicken and beef. The EU per kilogram of edible protein was higher for mealworms than for milk and chicken, and similar to values published for pork and beef. Both the GWP and the land use per kilogram of edible protein were lower for the mealworms than for the four benchmarks. The relatively high EU was due to the use of fossil fuels for heating the farm to suitable ambient temperatures. The impact of these heating requirements was largely offset in the GWP by an efficient feed utilization, which concomitantly limited the required amount of arable land. In a subsequent study, the water use of the aforementioned mealworm production system was quantified (Miglietta *et al.*, 2015). When expressed as litres per gram of animal live weight, the water use for the mealworms was higher than for chicken and pigs, but lower than for beef cattle. However, when expressed as litres per gram of edible protein, the water use was lower for mealworms (23 l/g) than for chicken (34 l/g), pork (57 l/g) or beef (112 l/g). The difference in ranking between these two units is caused by a higher protein content and greater edible portion of mealworms (100%), compared to the chosen benchmarks.

A second assessment of YM was based on a farm producing 17 t of larvae/year and used a cradle-to-mill-gate system border, including impacts of feed, farm and equipment (Thévenot *et al.*, 2018). Environmental impact was economically allocated over insect meal (88.5%) and oil (11.5%) based on yields and sales prices and expressed per kilogram of larvae meal, and per kilogram of protein (FUs). Feed production was a major driver of environmental impact (land use 87%, eutrophication potential (82%), acidification potential (66%) and GWP (48%)). The farming process was associated with 29% of the EU and 19% of the GWP. Most of the energy (56%) was used for drying the larvae. The impact of mealworm production in this assessment was lower than for the first (EU 24.29 vs 33.68 MJ, climate change 0.99 vs 2.65 kg CO_2-eq. and land use 1.60 vs 3.56 m^2). These differences are likely to reflect differences in the energy source (nuclear vs natural gas) and feed composition (wheat bran vs mixed grains with carrots).

The environmental impact of mealworm meal was higher for all investigated parameters compared to the utilized benchmarks for soya bean meal and fishmeal.

Cricket LCAs

Data from a Thai company, producing HC and two-spotted crickets in approximately equal proportions, was assessed from cradle to farm gate, including building construction materials (Halloran *et al.*, 2017). Edible mass and edible protein were used as FUs and the frass (insect faeces, often mixed with undigested feed and moulds) was considered a by-product replacing mineral fertilizer. The cricket farm was compared to a local broiler producer based on edible protein. Crickets have a higher crude protein content than broiler meat, therefore this FU is beneficial for the cricket production system. The GWP, including LUC was higher for broiler meat than for crickets (8.21 vs 4.35 kg CO_2-eq./kg edible protein). The eutrophication potential (freshwater, marine water and terrestrial) was approximately twice as high for broiler meat compared to crickets. Also, water depletion was higher for broiler meat than for crickets (0.94 vs 0.71 m^3/kg edible protein), whereas resource depletion, including minerals, fossils fuels and renewables, were similar (0.041 vs 0.043 g Sb-eq./kg edible protein). Feed production was the major driver of environmental impact.

A recent assessment based on a UK company, producing two-spotted crickets and BC for the UK pet food market, used a similar system border (cradle to farm gate) and also considered the produced frass as a by-product replacing mineral fertilizer (Suckling *et al.*, 2020). Weight of the live crickets was used as the FU. Feed production and cricket rearing were the main drivers of environmental impact. The GWP was 21.1 kg CO_2-eq./kg of cricket, of which 59% was attributed to the cricket rearing process, and 19% was due to heating. The far lower GWP of the Thai cricket farm (2.57 kg CO_2-eq./kg of cricket) (Halloran *et al.*, 2017) is due to the colder climate and higher control over climate conditions in the UK farm requiring more energy, thereby increasing the GWP. Furthermore, the UK study assumed that all carbon contained in the frass was emitted as CO_2 and, together with CO_2 from cricket respiration, these emissions were included in the GWP. These were excluded in the Thai study. Most studies exclude direct CO_2 emissions of insects and their frass as this carbon was first taken up from the air and stored as plant biomass, subsequently used as feed (Oonincx *et al.*, 2010; Oonincx and de Boer, 2012). Hence it is not a net contribution (emission) to GWP.

Furthermore, the UK system had a higher water resource depletion for crickets than the Thai system (0.82 vs 0.42 m^3/kg cricket), of which 99% was due to feed production. Here, the difference is likely due to the high feed conversion ratio (FCR) in the UK system (9.09 vs 2.50) indicating a very poor feed utilization rate. This factor potentially also underlies the six times higher freshwater ecotoxicity and 12 times higher freshwater eutrophication value for the UK system compared to the Thai system. Improvement of the FCR from the current 9.09 to 1.47 (Lundy and Parrella, 2015) would decrease freshwater eutrophication by 44%, LUC by 66%, and water resource depletion by 82%, indicating the large potential improvement due to better feed utilization.

Fly LCAs

Two species of flies have been assessed, the BSF (Salomone *et al.*, 2017; Mertenat *et al.*, 2019) and HF (van Zanten *et al.*, 2015). Data from an Italian pilot facility processing organic food waste with BSF larvae was assessed based on cradle-to-farm-gate data, excluding machinery and equipment (Salomone *et al.*, 2017). Three FUs were used: (i) tons of processed food waste; (ii) fat to replace rapeseed for biodiesel; and (iii) protein to replace soya bean meal in aquafeed. Frass was considered as a by-product replacing inorganic fertilizer. The mass of the organic food waste was reduced by 67% and associated with a GWP of 30.2 kg CO_2-eq./t of food waste. When corrected for avoided soya bean meal and nitrogen fertilizer, the GWP was -432 kg CO_2-eq./t of food waste. The GWP per kilogram of protein was 2.1 kg CO_2-eq. This was primarily (57%) due to assumed direct GHG emissions, which were derived from mass-based emissions from the methane-producing sun beetle larvae (Oonincx *et al.*, 2010). When calculating based on mass-gain data for that species the GWP was lower – 1.1 kg CO_2-eq./kg of protein. Recalculating the emissions, based on direct GHG emissions for BSF (Parodi *et al.*, 2020), indicates that direct emissions are approximately 95% lower than for sun beetle larvae which leads to a GWP of 0.91 kg CO_2-eq./kg of protein. This discrepancy is likely caused by the fact that contrary to sun beetle larvae, BSF larvae do not produce methane via gut-associated bacteria (Mertenat *et al.*, 2019). Therefore, direct GHG emissions are far lower, and hence the contribution to GWP is primarily due to transportation and drying of the larvae. Compared to the reported benchmark soya bean meal, the reported GWP was higher for BSF (2.1 vs 1.7 kg CO_2 eq./kg of protein). However, if based on the more accurate calculations above, the GWP would be lower for BSF (0.91 kg CO_2-eq./kg of protein) than for soya bean meal. The EU per kilogram of produced protein via BSF was 15.1 MJ which is much higher than for soya bean meal (4.1

MJ). The land use, however, was far lower at 0.05 vs 8.65 m^2/kg of protein (Salomone *et al.*, 2017).

An assessment based on an Indonesian facility treating biowaste with BSF compared their GWP with composting (Mertenat *et al.*, 2019). The produced larvae were considered an alternative to Peruvian fishmeal and the avoided methane emissions arising from the composting were included in this study. The latter was excluded in Salomone *et al.* (2017). Waste sourcing and compost utilization were considered outside the system border and indirect emissions due to infrastructure, equipment and machinery, as well as direct CO_2 emissions, were excluded.

The BSF treatment resulted in a far lower GWP than composting (35 vs 111 kg CO_2 eq./t of food waste). This result was partially due to the limited climate control (ventilation only) and due to the avoided methane formation. However, the GWP was not expressed per kilogram of larvae, larvae meal, or protein, which impairs further comparisons.

Another assessment of BSF utilized a cradle-to-gate approach and included several processing steps to transform fresh BSF to defatted protein concentrate (Smetana *et al.*, 2019). Dried distiller grains with solubles (DDGS) and wheat by-products were used as feed ingredients. Pureed BSF and defatted concentrate were used as FUs, as were fertilizer production and fat production, the latter to be used in pig feed. Per kilogram of fresh larvae, the calculated GWP was 1.16 kg CO_2-eq., with an EU of 17.9 MJ and a land use of 0.48 m^2. Various other indicators were summed together, which impairs direct comparison with other insect LCAs. However, the authors do conclude that plant-based protein is currently the most sustainable. The greatest contributors to all categories of environmental impact of pureed BSF were feed production (43%) and energy use (37%).

HFs were assessed by LCA in a theoretical system utilizing chicken manure and food waste as feed for the larvae which subsequently would be utilized as a pig feed ingredient (van Zanten *et al.*, 2015). The FU, 1 ton of dried and milled HF larvae, was associated with 770 kg of CO_2-eq., an EU of 9329 MJ and land used of 32 m^2. This study also calculated the indirect consequences of the system. The larvae meal was assumed to replace soya bean meal and fishmeal on a 50:50 basis and the food waste, currently used to generate bioenergy, would no longer be available for that purpose. Incorporating these effects decreased land use by 1713 m^2 but increased GWP by 1959 kg CO_2-eq. and EU by 21.342 MJ/t of HF larvae meal.

7.4 Effect of Feed

LCAs for insect production systems clearly indicate that the feed utilized for production is a primary driver of environmental impacts in such systems. Feed production is associated with land, water, and energy use, and GHG emissions. Inefficient use of feed also leads to more eutrophication, ecotoxicity and acidification. Feed utilization, expressed as the FCR (kilogram of feed/kilogram of produced mass), can vary greatly even for similar species.

Reported FCRs for HC and two-spotted crickets (2.50) (Halloran *et al.*, 2017), two-spotted crickets and BC (9.09) (Suckling *et al.*, 2020) and HCs (1.47) on broiler feed (Lundy and Parrella, 2015) indicate room for improvement. This could be achieved by better matching feed composition to the nutritional requirements of the insects, and by limiting feed losses. Also, harvesting at an optimal size, as suggested by Suckling *et al.* (2020), could decrease the FCR if not restrained by specific size requirements in the sales market.

Another way to decrease the environmental impact of insect production is to utilize underused feedstocks. Clearly, using waste products such as household waste or manure can hold much potential, if legally allowed and proven safe. Also using feed materials originally intended for conventional livestock but discarded due to contamination could improve the sustainability of insect production systems. As an example, grain products contaminated with mycotoxins are unsuitable for conventional production systems, but do not hamper the development of certain insect species (Bosch *et al.*, 2017; Camenzuli *et al.*, 2018). These mycotoxins seem to be catabolized by insects and therefore do not accumulate in the final product (Meijer *et al.*, 2019).

Similarly, some insect species are unaffected by certain heavy metals. Matching contaminated materials with species that efficiently excrete these heavy metals could allow the safe use of otherwise discarded substrates. For instance, cadmium-contaminated materials could be processed for YM and arsenic-contaminated materials could be used for BSF larvae (van der Fels-Klerx *et al.*, 2016). Further insights into the mechanisms utilized by these species to excrete or metabolize such contaminants are required, prior to utilizing these materials safely. However, when using troublesome waste products, it is essential that the insect species can use the material well to grow and develop. Studies on using polystyrene as feed for YM and wax moths indicate low growth rates and feed conversion efficiencies, indicating a low potential for commercialization (Billen *et al.*, 2020). Several by-products from the food industry have shown potential as insect diet ingredients and could decrease the environmental impact of insect production systems (Oonincx *et al.*, 2015; van Broekhoven *et al.*, 2015).

Besides utilizing by-products in insect production, the use of by-products from insect production can increase valorization and decrease environmental impact. If production is focused towards protein yields, the lipid fraction could be used as a biofuel (Wong *et al.*, 2018). Besides the insects themselves, the best known and most widely used by-product is insect frass.

Furthermore, frass might be a suitable substrate for anaerobic digestion and hence might function as an energy source, prior to being used as a fertilizer (Bulak *et al.*, 2020). Frass from mealworms, crickets and BSF larvae yielded 208–259 ml methane/g, which is comparable to benchmarks such as animal manures, organic wastes and sewage sludge, reported in that study. Subsequent utilization of the methane would reduce the need for fossil fuels as an energy source and thereby reduce EU and GWP, while retaining N, P and K in the substrate which could still be used as fertilizer.

7.5 Data Limitations

Within an LCA, decisions on the use of system borders, FUs, by-products and their allocation, and impact parameters are made. Different choices, for instance whether the purpose of a system is waste reduction or protein production, leads to different FUs, and the use of different benchmarks. Differences in system borders such as including construction materials, or utilizing residual materials as fertilizers, impair direct quantitative comparisons between publications. Also, variation in reported impact indicators and whether they are pooled or reported separately limits direct comparisons.

While the number of insect LCAs is limited, the aforementioned methodological differences made it necessary to include only the more commonly used indicators and focus on explaining the utilized system borders and FUs in this chapter. Hopefully in the coming decade, more detailed LCAs using similar system borders will become available allowing more direct comparisons. These would preferably utilize a cradle-to-farm-gate approach, several FUs and be based on large-scale production facilities. Moreover, in several LCAs on insects for food or feed, improved scenarios are explored (Halloran *et al*., 2017; Smetana *et al*., 2019; Suckling *et al*., 2020). These provide an outlook on the future regarding the potential development of an environmental impact. However, they should be interpreted with extreme caution as they often contain unproven assumptions.

7.6 Conclusions

Even though direct comparisons between the conducted studies are hampered, some relevant conclusions can be drawn regarding the sustainability of insect production. Land use associated with insect production generally seems low, compared to conventional feed and food products. The EU (expressed as fossil fuel depletion) of insect production is often high compared to conventional products. To a large extent this is because several LCAs have been conducted for systems in temperate climates, which require extensive climate control. This also leads to an elevated GWP due to the emission of GHGs associated with the used energy. Besides energy consumption during the rearing process, a large part of the environmental impact is due to the production of feed for the insects. This effect can be mitigated by using lower impact feed sources, assuming that feed can be used efficiently, thereby decreasing the environmental impact associated with insect production.

As large-scale insect production systems are relatively new and rapidly developing, it seems reasonable to expect increased efficiency and thereby decreased environmental impact as the sector progresses.

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8 By-products of Insect Rearing: Insect Residues as Biofertilizers

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8.1 Introduction

Insects are increasingly promoted and reared across the world generating high quantities of insect biomass and rearing residues commonly referred to as insect 'frass'. Black soldier fly (BSF; *Hermetia illucens*) larvae (BSFL), house fly (HF; *Musca domestica*) larvae (HFL) and yellow mealworm (YM; *Tenebrio molitor*) represent the most popular species used for the large-scale bioconversion of diverse organic wastes. Several recommendations indicate that the frass produced by these insects has potential use as a biofertilizer in farming due to their nutritional content and associated beneficial microbiota. However, in contrast to compost, vermicompost and even bokashi technologies, the ability of insect frass to enhance soil health and crop productivity is poorly understood. In addition, while crustacean-derived chitin is known to be an effective elicitor of plant defence responses, relatively little is known about the potential value of insect chitin in plant priming. This chapter reviews the information available on the value of insect frass as biofertilizer with a focus on soil nutrient replenishment and soil organic matter maintenance. Beneficial effects upon plant growth and nutritional performance induced by the addition of insect frass to soils are compared to that of conventional biofertilizers and inorganic fertilizers. Finally, the potential for insect chitin to prime plant defences via the induction of systemic resistance is discussed.

The large-scale rearing of insects is recognized by scientists, agricultural organizations and industries across the world as a promising circular economy approach to mitigate food insecurity. Insects play an increasing role in the sustainable valorization of organic waste, producing insect biomass for food and feed as well as insect frass, that has value as a source of nutrient-rich organic matter for agriculture (Pastor *et al*., 2015; Bloukounon-Goubalan

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et al., 2019a; Fowles and Nansen, 2020). BSFL can convert organic food waste, animal manure, municipal organic waste, dewatered faecal sludge or straw residues into organic value-added products (Diener *et al*., 2011; Wang *et al*., 2016; Sarpong *et al*., 2019). HFL can decompose animal manure, agro-processing by-products or a mix of food waste and straw producing frass that can be used as a soil conditioner (Niu *et al*., 2017; Bloukounon-Goubalan *et al*., 2020). YM fed exclusively on wheat bran, can transform it into a complete fertilizer, a substitute for mineral nitrogen, phosphorus and potassium (NPK) fertilizer (Houben *et al*., 2020).

Chitin, residing in the cuticles and gut lining (peritrophic membranes) of insects, is transferred via larval moulting during the rearing process into frass residues and has potential to play an important role in plant defence against pests and pathogens. Chitin, and its deactylated derivative chitosan, have been shown to induce plant defence responses indirectly via supporting the proliferation of pathogen-inhibiting microorganisms in the soil, and directly *in planta* via: (i) ion flux variations; (ii) cytoplasmic acidification; (iii) membrane depolarization and protein phosphorylation; (iv) chitinase and glucanase activation; (v) lignification; (vi) generation of reactive oxygen species; (vii) biosynthesis of jasmonic acid and phytoalexins; and (viii) the expression of early responsive and defence-related genes in both monocotyledons and dicotyledons (Pusztahelyi, 2018).

Such ecosystem services offered by insects prove that they have the potential to revolutionize conventional agriculture. However, there is a need to conduct further research to fully understand the value of frass associated with insect rearing as a biofertilizer and its viability at a range of scales from smallholder to large commercial farms. The potential of chitin-supplemented organic fertilizer to improve plant immunity must also be elucidated for the benefit of mainstream agriculture.

The goal of this chapter is to highlight the potential benefits associated with the use of insect-rearing residues as biofertilizers while exploring the mechanisms by which chitin in insect frass might control common crop pathogens.

8.2 Potential Benefits for Soil Fertility Derived from the Use of Insect Frass

Soil nutrient supply

Due to nutrient-limiting constraints in most cultivated soils, the application of an organic material aims to improve nutrient supply and maintain soil organic matter for as long as possible. Therefore, when applying an organic material to soil, the rate of nutrient mineralization ‘release’ must be adequate to supply the amounts of nutrients required for efficient plant growth. To date, understanding of nutrient mineralization from insect frass is limited to a few *in-situ* incubations or buried bag trials. Bloukounon-Goubalan *et al*. (2019a, b) and Houben *et al*. (2020) reported relatively rapid mineralization of organic carbon (C) and other nutrients when they assessed the decomposition and nutrient release patterns of fly-degraded manures and YM wheat-bran-rearing residues (Fig. 8.1, Table 8.1). Organic nitrogen (N) mineralization rates increased in the following order (where *k* is the mineralization rate of nitrogen from insect frass in the soil): YM frass < HFL frass from poultry and sheep manure (*k* = 0.0027/day) < BSFL frass from soya bean bran and maize (corn) bran (*k* = 0.007/day) < BSFL frass from maize bran (*k* = 0.008/day) < BSFL frass from soya bean bran and maize hull (*k* = 0.011/day) < HFL frass from poultry and cow manure (*k* = 0.017/day) < HFL frass from pig manure (*k* = 0.018/day) < HFL frass from poultry and pig manure (*k* = 0.018/day) < HFL frass from poultry manure (*k* = 0.02/day). As rapid N release could reduce the need for N input in the form of mineral fertilizer, incorporation of these manures into agricultural soils will provide energy and N for microbial activity and plants in the short term (Li and Li, 2014; Abbasi *et al*., 2015; da Silva *et al*., 2020). In terms of N supply, YM frass and fly larvae frass from maize bran, soya bean bran or a mixture of soya bean bran and maize bran provided the highest amount of N for short-duration crops. There is, however, the need to supplement them with P and K from inorganic sources to ensure full nutrient requirements for crops are met. If dependent only upon these biodegraded substrates to meet the plant's P or K requirement, the large amounts of N-rich substrates required would lead to N loss through either leaching as nitrate (NO_3) or emission as gases (nitrogen dioxide (N_2O), nitric oxide (NO) and ammonia (NH_3)). None the less, these biodegraded substrates from maize bran, soya bean bran or a mixture of soya bean bran and maize bran are a good source of calcium (Ca) and magnesium (Mg) for plants and could improve soil cation exchange capacity when well managed. As N is a limiting nutrient and P availability is low in most cultivated soils, HFL frass from poultry manure is the most complete organic fertilizer as it also provides well-balanced NPK (1-1-1) and in sufficient amounts to meet the needs of short-duration crops without the need for additional inorganic fertilizer. HFL frass from pig manure has the same potential NPK (1-1-1) as HFL from poultry manure but there is the need to incorporate twice the equivalent amount of biodegraded poultry manure to grow crops which have a 3-month growing period. Furthermore, the residual effect of HFL from pig manure has the advantage of being suitable for longer growing season crops (i.e. those with maturity periods above 6 months).

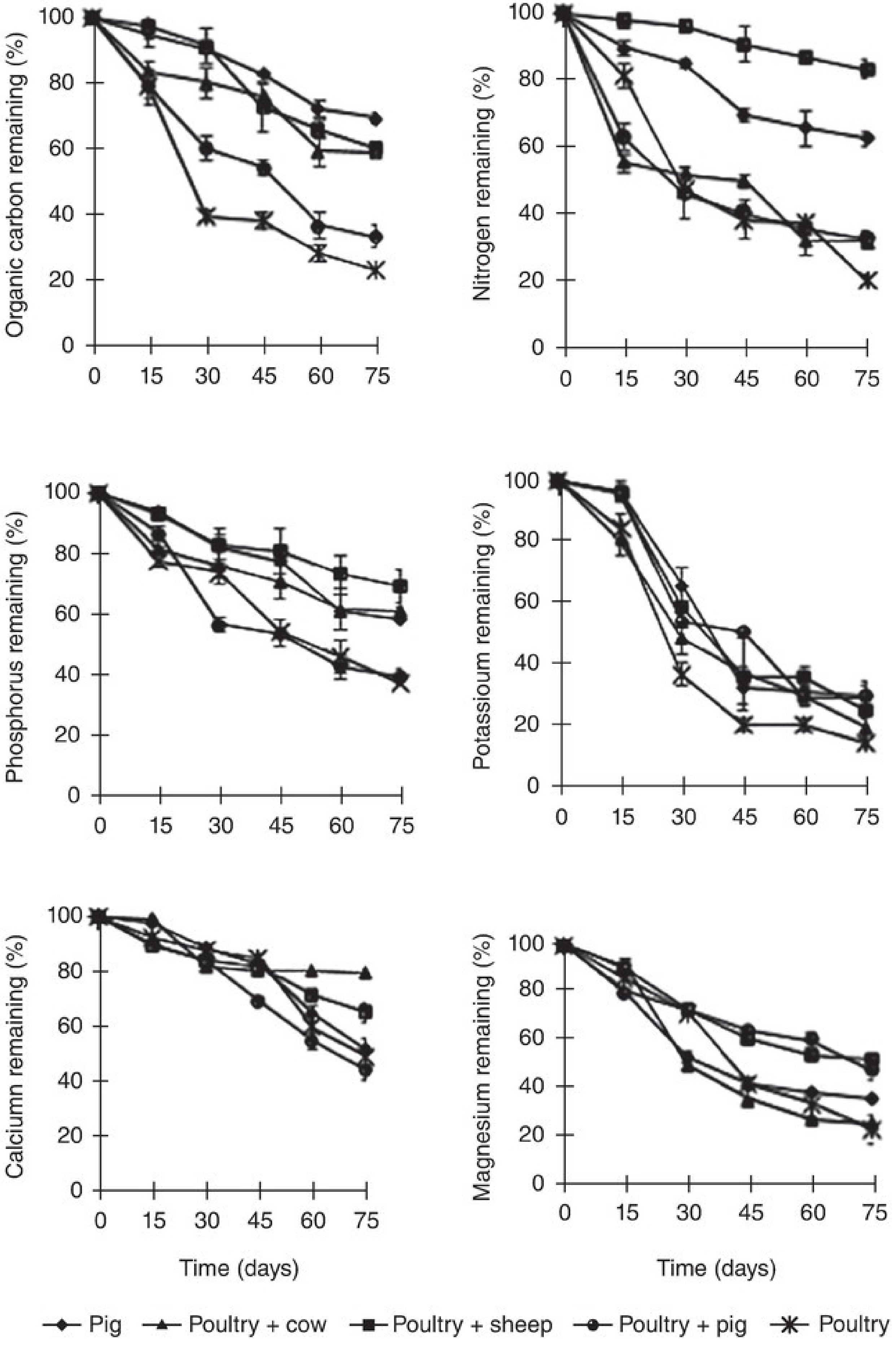
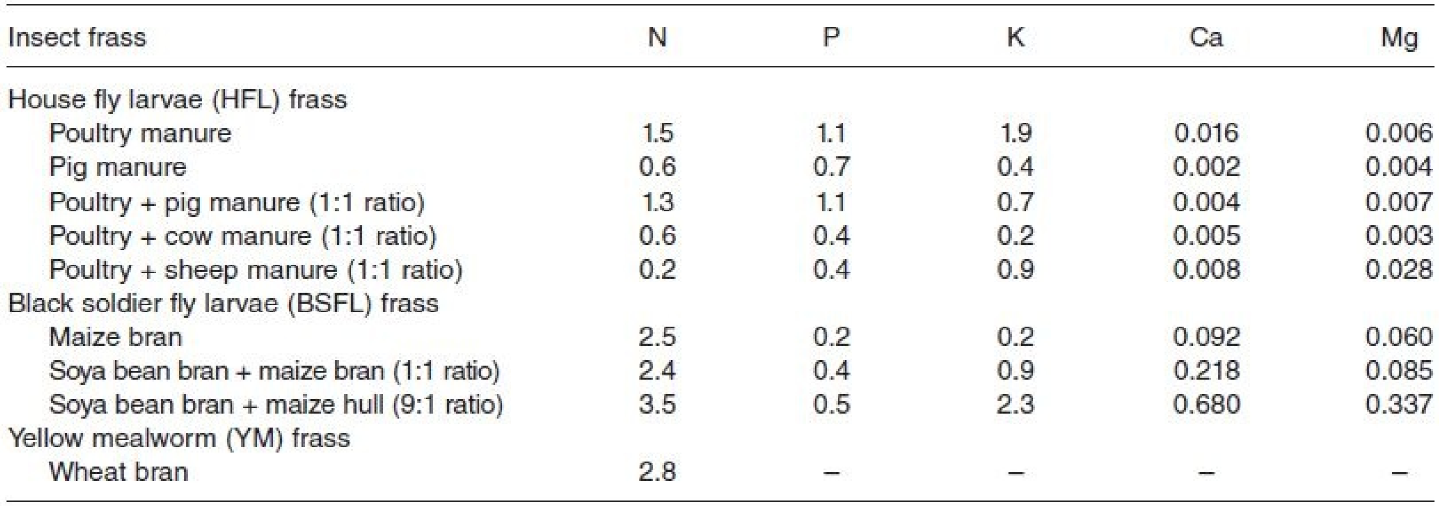


Fig. 8.1. Nutrient content changes in manures previously biodegraded by fly larvae during mineralization in soil. From

Bloukounon-Goubalan *et al*., 2019a.

Table 8.1. Amount of nutrient supplied in kilograms per 100 kg of manure incorporated in Acrisol (reference soil) within 3 months. From Bloukounon-Goubalan, 2019, and Houben *et al*., 2020.



Insect frass	N	P	K	Ca	Mg
House fly larvae (HFL) frass					
Poultry manure	1.5	1.1	1.9	0.016	0.006
Pig manure	0.6	0.7	0.4	0.002	0.004
Poultry + pig manure (1:1 ratio)	1.3	1.1	0.7	0.004	0.007
Poultry + cow manure (1:1 ratio)	0.6	0.4	0.2	0.005	0.003
Poultry + sheep manure (1:1 ratio)	0.2	0.4	0.9	0.008	0.028
Black soldier fly larvae (BSFL) frass					
Maize bran	2.5	0.2	0.2	0.092	0.060
Soya bean bran + maize bran (1:1 ratio)	2.4	0.4	0.9	0.218	0.085
Soya bean bran + maize hull (9:1 ratio)	3.5	0.5	2.3	0.680	0.337
Yellow mealworm (YM) frass					
Wheat bran	2.8	–	–	–	–

Soil organic matter maintenance

Soil organic matter contributes to soil productivity in many ways and comprises plant residues, living microbial biomass, detritus (active organic matter) and humus (the final product of decomposition). Most productive agricultural soils contain 3–6% organic matter. Published values for organic C (a measurable component of organic matter) in insect frass range from 40% to 56% suggesting its significant potential to improve soil organic matter (Zhang *et al*., 2012; Zhu *et al*., 2015; Houben *et al*., 2020). However, frass derived from different insect-rearing substrates have diverse patterns of C mineralization in the soil that determine their contribution to soil organic matter. For example, 77% of organic C was mineralized within 75 days in degraded Acrisols (reference clay-rich soil associated with humid, tropical areas) supplemented with HFL frass from poultry manure (Bloukounon-Goubalan *et al*., 2019a). Lovett and Ruesink (1995) showed that the C mineralization rate of gypsy moth frass was greatest in the first 10 days during a 120-day trial and mealworm (MW) frass lost 40% of its initial mass after just 1 week of incubation (Kagata and Ohgushi, 2012).

By contrast, the organic C in fly larvae frass from pig manure was found to be resistant to soil microbial degradation with only 39% of the organic matter mineralized within 75 days in soil (Bloukounon-Goubalan *et al*., 2019a). Wang *et al*. (2016) showed that the humification index (HI) (which is a measure of dissolved organic matter (DOM)) of pig manure during biodegradation by HFL increased from 0.25 to 0.52 within 6 days. The authors concluded that enhanced biodegradation of DOM and the subsequent formation of humus in the HFL frass from pig manure led to a high level of aromaticity and humification under HFL bioconversion, generating a stable bioproduct. None the less, this HI was lower than that recorded in compost from a mixture of poultry manure, cotton waste, olive and mill waste (HI: 8.7) or in compost from a mixture of pig slurry, poultry manure and sweet sorghum bagasse (HI:18.5) (Bernal *et al*., 1998). Bloukounon-Goubalan *et al.* (2019a) showed that the nutritive lifetime of HFL frass from pig manure did not exceed 100 days therefore the organic fraction could be depleted in the soil within a year. According to De Neve *et al.* (2003), stable organic matter in an organic material is the fraction remaining in the soil after 1 year. Thus, insect frass is biologically more 'active' and acts as a labile food source for the soil microbiome. The high content of easily mineralizable C is beneficial to soil microorganisms as it improves microbial biomass and activity, changes the microbial community structure and composition, and enhances the growth of specific beneficial organisms such as actinomycetes and arbuscular mycorrhiza fungi (D'Hose *et al*., 2016). Overall, this suggests that insect frass should be considered as labile rather than stable organic matter, providing short-term (< 1 year) organic matter turnover, energy and nutrients for soil microorganisms and nutrients for crop growth (Strosser, 2010; Xiao *et al*., 2015).

The ideal C:N ratio to support the proliferation of soil microorganisms is 24:1. In general, the C:N decreases in animal manure during bioconversion by fly larvae as they break down the organic materials into carbon (in the form of CO_2) and nitrogen (as N-NH^+_4 and N-NO^-_3). Coulibaly *et al*. (2020a) recorded a decrease of 8.8% and 8.4% in C and N, respectively, in poultry manure after three successive cycles of biodegradation by fly larvae. Bloukounon-Goubalan (2019) showed that the C:N ratio of HFL frass from poultry, pig and guinea fowl manures were 6, 8 and 12, respectively, after three successive cycles of larval biodegradation. Application of this frass increases N concentration in soil for plant and microbial growth and encourages mineralization processes (Bloukounon-Goubalan, 2019; Bloukounon-Goubalan *et al*., 2019a). However, a C:N ratio of > 20 in cow manure degraded by HFL could induce N immobilization if applied on N-deficient soils. None the less, BSFL decomposed cow manure effectively, transforming its C:N ratio from 22 to 15 (Liu *et al*., 2019). Knowing the high content of phenolic compounds in cow manure, BSFL frass from cow manure could last longer in soils than those from pig and poultry manure and thus could contribute efficiently to biologically stable organic material.

In addition to providing C for soil microbes, insect frass application offers a means of enhancing soil microbial biomass. In fact, the insect gut microbiome is rich in *Bacteroidetes*, *Proteobacteria*, *Firmicutes*, *Fusobacteria*, *Actinobacteria*, *Enterobacteriaceae*, *Providencia*, *Pichia*, *Geotrichum* and *Trichosporon* enabling them to digest a diverse range of wastes (Zhao *et al*., 2017; Liu *et al*., 2019). Some humus and soil-feeding bacteria have been identified in organic material during rearing of HF (Zhao *et al*., 2017) proving that they have been transferred from the larval gut to the rearing substrate. Knowing that soil-living organisms provide the basic necessities of life (food, shelter and water) to perform functions required to produce food and fibre, the application of insect frass to the soil is an effective way to improve soil health.

While insect frass application is beneficial to soil health, unfortunately it can also have negative effects if the timing is not right and amounts applied do not meet the requirements for plant and soil microbial growth. This is crucial as insect frass is N rich and applications must be low enough to avoid groundwater and atmospheric contamination. We recommend that the application rate be determined from the mineralizable N in the frass during the vegetative period of the crop. For a continuous application, we assume that insect frass supplementation in C-poor soil will enhance microbial biomass.

8.3 Comparison of Quality of Insect-derived Biofertilizers vs Common Organic and Inorganic Fertilizers

Effect on plant growth and nutrition

To date, few studies have investigated the effect of insect frass on plant nutrition and growth. Mason (2020) showed that BSFL frass applied in sand peat at rates of 4% and 8% led to 94.5% and 97.5% successful barley seed germination, respectively, as compared to 87% with NPK (20-20-20). The author found that 4% (w/w) of potting mix achieved the best results in terms of above-ground biomass production, chlorophyll (indicative of respiratory capacity), and Brix value (a measure of the amount of dissolved plant sugar established using a refractometer; it is an indicator of plant health). It is known that increasing the H^+ ion concentration in soils has an adverse effect on seed germination.

As insect frass has an alkaline pH (from 8 to 10), their incorporation in soil reduces soil acidity and can thus enhance seed germination. Moreover, humic acid and Ca content in the BSFL frass could have positive effects on seed germination. Wu *et al.* (2020) also found a significant improvement in chlorophyll content, and an increase in above-ground biomass and yield of rice plants by 40% and 50%, respectively, with 4% BSFL frass from poultry manure as compared to the unfertilized treatment. Bloukounon-Goubalan (2019) showed that HFL frass from poultry manure applied at 4 t/ha increased amaranth height and stem girth growth rates by twofold, as compared to the unfertilized treatment (Fig. 8.2). Undecomposed poultry manure applied at the rate of 10 t/ha and 20 t/ha increased amaranth height and stem girth growth rates by 1.5-fold and 2.8-fold, respectively (Mshelia and Degri, 2014; Okoli and Nweke, 2015). In addition, undecomposed pig manure applied at 90 kg N/ha increased amaranth growth rate (1.3-fold by height) (Iren *et al*., 2016) while HFL frass from pig manure applied at 75 kg N/ha increased amaranth height growth rate by threefold (Bloukounon-Goubalan, 2019). Zahn (2017) comparing the effect of 15 t/ha of compost and 5 t/ha of BSF frass, found relatively similar plant height median.

Fig. 8.2. On-farm experiment of *Amaranthus hybridus*, 20 days after transplanting and fertilized with various sources of fly larvae frass, applied at a rate of 75 kg N/ha. (a) A panoramic view of the trial; (b) the control plot (no larvae frass); (c) the plot fertilized with BSFL frass reared on a mixture of soya bean and maize hull; and (d) HFL frass reared on a mixture of poultry and sheep manure. From Bloukounon-Goubalan, 2019.

The improved performance of plant growth in the presence of insect frass, even when applied at lower rates, was comparable with results from similar sources of non-biodegraded material, and is due to both increased P and K content in the frass through biodegradation processes and the rapid mineralization of organic N. Kagata and Ohgushi (2012) also found a positive effect of cabbage looper *Mamestra brassicae* frass on *Brassica rapa* above-ground biomass and leaf N uptake and they attributed these findings to the high nutritive value of the frass. Poveda *et al.* (2019) concluded that positive effects of YM frass on plant growth were partly attributable to the presence of plant growth-promoting microorganisms (especially *Firmicutes*, *Proteobacteria*, *Ascomycota*) in the faeces. Moreover, the low humic acid content in insect frass as compared to common compost could enhance mineral nutrient uptake by plants via increasing the permeability of root cell membranes (Türkmen *et al*., 2014).

Published data suggests that insect frass is more efficient than mineral fertilizer in relation to affording the durable replenishment of soil fertility. Although the positive effect of mineral fertilizer applications on plant growth is clear, these fertilizers do not provide soil organic matter and can negatively affect soil quality in the longer term. In addition, long-term repeated applications of inorganic fertilizer on soils with poor organic matter content can lead to soil acidification as ammonium-based fertilizers acidify soil (by generating 2H^+ ions for each ammonium molecule nitrified to nitrate). By contrast, applications of insect frass provide more readily available soil nutrients as compared to inorganic fertilizer (Bloukounon-Goubalan *et al*., 2019a).

Coulibaly *et al*. (2020b) have shown that over large production areas, the application of residues of maggot production in combination with reduced (half-dose) mineral fertilizer application (75 kg/ha of NPK and 25 kg/ha of urea), improved maize production and induced positive effects on soil fertility. Increases of maize grain yield by 84% and 38% as compared to control (without fertilizers) and fertilizer (150 kg/ha of NPK and 50 kg/ha of urea)-treated soils, respectively, suggest this approach could utilize low volumes of currently available frass and reduce mineral fertilizer costs.

Profitability, timing efficiency and on-farm advantage of insect frass

Waste bioconversion by insects is an ecosystem service that transforms low-value organic waste into high-value insect protein and high-value biofertilizers. The production of insect frass takes less time as compared to any other bioconversion process (Table 8.2). In fact, while management of anaerobic composting of waste is costly, and aerobic composting takes more than 90 days, bioconversion by HFL takes just 4–7 days, 14–25 days using BSFL and 30–45 days using YM. In addition, total NPK contents are higher in insect frass as compared to the initial fresh material as P and K increases in the frass during the bioconversion process. Although N content decreases during the rearing process, it has been shown that most of the N in insect frass is in organic form (Bloukounon-Goubalan, 2019). Insect frass appears also to be profitable as larvae or insects are sought in animal protein markets for animal feed. Joly and Nikiema (2019) reported that the cost of BSFL ranged from US$200/t of larvae meal to US$2000/t, and an average of 200 kg larvae/t waste can be harvested.

Table 8.2. Nutrient content in diverse biofertilizers including insect frass.

Source of organic fertilizers[a]	Process duration (days)	Total nutrient content (%)			References
		N	P	K	
Traditional pig manure		1.7–2.1	0.6–1.9	0.4–0.5	Bloukounon-Goubalan (2019)
BSFL frass from pig manure	9	2.4–2.6	2.1–3.9	0.9–1.1	Oonincx *et al*. (2015), Liu *et al*. (2019)
HF frass from pig manure	5	1.6–2.2	1.1–2.8	0.6–0.8	Zhang *et al*. (2012), Bloukounon-Goubalan (2019)
Vermicompost from pig manure	112	1.8	–	0.4	Atiyeh *et al*. (2001)
Traditional poultry manure		1.9–2.4	1.0–2.2	1.1–2.4	Beohar and Srivastava (2011), Liu *et al*. (2019)
BSFL frass from poultry manure	9	1.4–2.3	1.1–1.8	1.9–2.1	Oonincx *et al*. (2015), Liu *et al*. (2019)
HF frass from poultry manure	4	1.8–2.0	2.5–3.6	2.3–3.2	Bloukounon-Goubalan (2019)
Vermicompost from poultry manure	45	0.2	0.6	0.3	Beohar and Srivastava (2011)
Traditional wheat bran		0.4	0.01	0.2	Abbas *et al*. (2012)
MW frass from wheat bran	30	0.5	0.2	0.2	Houben *et al*. (2020)
Bokashi from wheat bran	50	2.4	0.4	0.6	Christel (2017)

[a] BSFL, black soldier fly larvae; HF, house fly; MW, mealworm.

None the less, to have more understanding of the profitability of insect bioconversion innovation, deep economic analysis considering infrastructure, energy, insectarium costs, the scale and the goals of the bioconversion is required. Moreover, insect frass is unique as a biofertilizer being the only readily available source of chitin for plants. Chitin has been shown to enhance plant resistance to pests and pathogens, as well as enhancing the proliferation of beneficial microbes (Sharp, 2013). Thus, insect frass could not only reduce inorganic fertilizer use but also has potential to enable a reduction in pesticide use.

8.4 Insect Frass and Plant Health Improvement

Chitin (poly 3-1,4-*N*-acetylglucosamine) is a N-containing polysaccharide in which the basic unit is an amino sugar and is found in fungal cell walls, insect exoskeletons, and shells of crustaceans and nematode eggs. Crustacean shell waste contains a greater 200–300 g/kg chitin (Arbia *et al*., 2013) as compared to 0.01–0.14 g/kg in adult crickets, waxworm larvae, MW, HFL and BSFL (Finke, 2007). However, chitin in crustacean cuticles is tightly associated with inorganic salts such as calcium carbonate, proteins, oil and pigments (Gortari and Hours, 2013). As the chitin is trapped in calcified shells, its isolation requires a complex chemical process. By contrast, insect chitin is in a form that can be broken down naturally by plant chitinase enzymes that are induced as a part of the immune response to pathogen attack. Diener *et al*. (2009) reported that insect frass contains traces of chitin and is a valuable supplement for soil.

Chitin amendment and soil microorganism growth affecting plant immunity

The addition of chitin to soils affects the soil microbiome and plant rhizosphere. Several studies report that soil supplementation with chitin stimulates microbial activity under oxic and anoxic conditions in agricultural soil slurries (Jacquiod *et al.*, 2013; Wieczorek *et al.*, 2014). Modulation of the root microbiome by plant molecules in response to various abiotic and biotic stresses is well documented and includes the induction of many plant growth-promoting rhizobacteria (PGPR) of the genera *Bacillus* and *Serratia* and plant growth-promoting fungi of the genera *Trichoderma*, *Fusarium* and *Serendipita* (Pascale *et al.*, 2019). Debode *et al*. (2016) showed that the addition of crustacean chitin to soil increased > 10-fold the relative abundance of PGPR and other rhizosphere microorganisms (including members of the genera *Cellvibrio*, *Pedobacter*, *Dyadobacter*, *Streptomyces*, *Lecanicillium* and *Mortierella*) reported to be involved in the N cycle and chitin degradation. Sarathchandra *et al*. (1996) assessed the effects of soil amendment with crab-shell chitin on populations of soil bacteria and fungi and found that chitinolytic fungi such as *Trichoderma hamatum*, *Gliocladium* spp. and *Verticillium lecani* increased 2.5-fold in soil while bacteria such as *Serratia liquefaciens*, *Xanthomonas maltophilia* and *Enterobacter gergoviae* increased 13-fold as a result of the addition of chitin. Moreover, De Tender *et al*. (2019), in evaluating peat substrate amended with crab-shell chitin responses in the lettuce rhizobiome, found that fungal genera *Hanseniaspora* and *Mortierella*, and a number of bacterial operational taxonomic units (OTUs) such as *Cellvibrio*, *Escherichia* and *Nitrosospira* increased significantly upon chitin addition. As insect frass contains the only plant-digestible form of chitin, its application should increase the number of chitinolytic microorganisms present in soil and the plant rhizosphere thereby inducing plants to produce the enzyme chitinase, which will in turn break chitin present in soil plant pathogens into N and chitosan, resulting in mortality and a decrease in pathogen populations. Furthermore, BSFL frass can contain a remarkable spectrum of antimicrobial peptides that exhibit diverse inhibitory effects on various pathogens (Boccazzi *et al*., 2017).

Plant-amended insect frass effect on pest control

Unlike conventional manures and composts, insect frass contains chitin derived from moulted exoskeletons. Very few studies have investigated the effects of insect frass application on plant responses to pathogen attack, whereas a relatively large number of studies have examined the effects of crustacean-derived chitin upon plant and soil health. Choi and Hassanzadeh (2019) found that the fungal pathogens *Rhizoctonia solani*, *Fusarium oxysporum* and *Pythium myriotylum* were unable to grow in soil amended with BSFL frass. Similarly, Elissen *et al*. (2019), who examined disease suppression by BSFL frass amendment, found that application of 1.5% BSFL frass reduced by half *P. myriotylum* infection on cress plants. Observations of disease suppression in plants could be linked to shifts in microbial community composition and activity, which can naturally suppress many plant diseases by inducing immune responses in plants (Manjula and Podile, 2001; Hadwiger, 2013).

Chae *et al*. (2006) found that adding 30% crab-shell chitin to compost inhibited the development of late blight (caused by *Phytophthora capsici*) on pepper as compared to a control compost-only treatment. In addition, root mortality was found to be 87% less in pepper plants growing with chitin compost as compared to the control and just 9 days after the introduction of *P. capsici*, the rhizosphere chitinase activity in chitin-treated compost was 65% greater than that in the common compost. Sid Ahmed *et al*. (2003) found similar results by comparing the effect of 0.5% shrimp-derived chitin upon biological control activity of *Bacillus* spp. and *Trichoderma harzianum* against root rot disease in pepper plants and reported that 0.5% chitin reduced *R. solani* and *P. capsici* disease severity by at least 64%.

Collectively published data, while derived primarily from studies using crustacean-derived chitin, provide evidence to suggest that even though insect frass contains less than 1% chitin, their application to soil can stimulate plant systemic resistance. Indeed, the presence of insect chitin around plant roots generates the perception of a predator's presence, thereby stimulating an immune response that triggers a multitude of effects including the establishment stronger cell walls, reinforcing external structures and/or increasing the translocation of nutrients and other compounds involved in protection. Nutrients travel more rapidly through the circulatory system to grow thicker stalks and stems, and increased turgor pressure pushes metabolites through the roots and leaves to suppress plant pathogens and diseases. Enzymes and alkaloids, toxic to plant-eating insects are produced and circulated throughout the plant, so that when native insects feed on the plant, they ingest plant-produced poisons that disrupt their digestive systems, thus acting as a biopesticide.

8.5 Conclusions

While more research is essential to understand the true value of insect-derived biofertilizers for plant and soil health, preliminary findings suggest there are significant opportunities for beneficial impacts in agriculture and horticulture to be realized. Along with large-scale commercial insect production will come significant volumes of frass, which may provide the opportunities to reduce the use of chemical fertilizers, pesticides and fungicides, making a positive contribution to the sustainable production of food and feed.

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9 Insect Production and Utilization of Insect Products in Asia

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Most often, when the topic of insects in Asia is tackled it is related to entomophagy (insects as human food). As such, there is a plethora of published scientific and non-scientific articles available (reviewed by Yen, 2015). However, there is very little published information about the uses of insects for pets and livestock in Asian countries.

Those who have been wandering around the streets of Bangkok (Thailand) or Siem Reap (Cambodia) for example, would certainly remember the hawkers selling all sorts of fried insects to snack on. Those who have ventured a little bit further in popular neighbourhoods in China, Indonesia or Malaysia would have noticed that pet shops swarm with exotic animals. Besides ordinary dogs, cats or rabbits, it is even more common in Asia to own pet reptiles or amphibians such as snakes, geckos, chameleons, frogs, toads or tortoises. People also fancy small exotic mammals (hedgehogs, chinchillas, monkeys, sugar gliders), expensive ornamental fish and songbirds. Exotic pet owners are very attentive to the feed quality they buy as it contributes to the well-being of their valued animals. This is why it is very easy to buy live insects such as grasshoppers, crickets, mealworms, cockroaches or superworms in pet shops or markets all around Asia where they are sold by weight (a few cents for 10–20 g) or per insect for larger species. Insects are known to provide protein, vitamins and other essential nutrients to animals who naturally consume them. Contrary to Western countries where insects would generally be processed into meals to be incorporated into conventional pet-food products (complete feed or treats), trends in Asia remain mostly to feed whole insects live to pets. Wild-caught insects such as locusts, grasshoppers and termites are still very much used in China to feed birds and poultry (Feng *et al.*, 2018). In Indonesia, the harvest of Asian weaver ant (*Oecophylla smaragdina*) pupae and larvae from plantations or forest trees is part of numerous rural family livelihoods; fresh or boiled and sun-dried ‘kroto’ as they are called, are sold as feed for songbirds or as fish bait (Césard, 2004). In South-east Asia, fluorescent lights are commonly hung above fish cages or ponds on both small family and larger commercial farms to attract insects at night and this can make a significant contribution to farmed fish diets.

Insects sold in pet shops are usually supplied from intermediate retailers or directly from individuals that catch them from the wild or breed them at a small scale. Online retail of insects as feed for pets is also expanding in Asia. This trading strategy, less suitable for live insects due to the risk of mortality during transportation, has offered opportunities to the

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entrepreneurs of Probugs Feeds to develop innovative products and marketing approaches. They have patented ‘eco-fresh insects’: farm-raised insects preserved under vacuum-sealed packaging which guarantees the preservation of the flavour, moisture, texture and nutritional quality of the insects for live feeding. This type of business relies on insect farms as it promotes sustainability and requires a constant supply in terms of volume and quality. Domestication of selected insect species is key to answer the growing demand for feed (and food), as it may limit the impact on resources and the environment. Insect farms with varying production capabilities are burgeoning all around Asia. Traditional farming models apply semi-domestication methods which consist of manipulating the insect habitat to improve its productivity (Chen *et al*., 2009); this model contributes significantly to boost incomes and improve the livelihoods of rural populations. When they are not sold on markets or to retailers, sun-dried or live insects often serve as a complementary feed for livestock (poultry, swine or fish) reared on small-scale rural farms (Fig. 9.1). Complete animal feed may not be readily available in rural or isolated areas and the cost of commercial complete feed can be prohibitively high, therefore insect domestication or semi-domestication provides a potentially longer-term resilient feed supply for these farmers.

Fig. 9.1. Chickens feeding on housefly larvae. Photo courtesy of CABI.

Medium- and large-scale insect farming industry, where colonies are bred in captivity under a controlled or semi-controlled environment, is not novel in Asia. Cockroaches, crickets, honeybees and silkworms have been farmed for food, feed or medicine for decades in China and Thailand for instance. Also China produces large volumes of dried, canned or powdered yellow mealworms (*Tenebrio molitor* L.) and superworms (*Zophobas morio*) as feed for domestic and export pet and poultry markets (Yi *et al*., 2010; Feng *et al*., 2018). Farmed soft-shelled turtles, eels and poultry are also commonly fed with locally farmed housefly larvae (*Musca domestica*) reared on animal manures in China (Zhang *et al*., 2008).

The rising global demand for alternative protein sources for animal feed is leading to worldwide industrialization of the sector. Over the last 10 years, several companies developing farming systems to produce black soldier fly (BSF; *Hermetia illucens*) larvae and derivatives have appeared in Malaysia (Entofood, Nutrition Technologies, Betsol, Unique

Biotech), China (JM Green, Guangzhou Unique Biotechnology), Singapore (Protenga, Insectta) Vietnam (Entobel), Indonesia (Biocycle, Nusa Origin, Magalarva) and South Korea (Nutri Industry). The recent investments in technologies developed by these companies highlight the interest and the potential for this tropical species which can bio-convert a wide range of organic products into protein and fat. Asia is a strategic location for the establishment of industrial BSF farming systems for two reasons. First, it is a major hub for commercial aquaculture and livestock farming, therefore regional demand for feed and feedstuffs is high and constantly growing. Secondly, large volumes of poorly valorized agro-industrial by-products and food waste is generated annually in Asia, which represents a unique opportunity for industrial BSF farmers to source large volumes of feedstocks year-round to produce the insect larvae. Besides, some of the companies that have already developed insect farming systems in other geographic areas (Europe, North America or Africa) are looking at expanding their activities in Asia where production costs are competitive and business opportunities are infinite.

The processing technologies used at this scale vary from simple drying (static or microwave oven, spray drying, disc drying, etc.) to more advanced fractionation technologies depending on the target market, customer demand and company strategy.

Asia has a long history of using insects obtained through wild harvesting or simple farming for pet food and animal feed. These traditional practices, often used for subsistence in poor rural areas, will certainly perpetuate while the sector also continues its expansion towards industrialization in order to answer the regional and global demand for feed ingredients.

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10 Insect Production and Utilization of Insect Products in Africa

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The insects most commonly utilized in animal feed in Africa are termites. Several genera, mainly *Macrotermes*, *Odontotermes* and *Trinervitermes* are traditionally collected or trapped by smallholder farmers in sub-Saharan Africa to provide a protein source for chicken, guinea fowl or turkeys (Fig. 10.1). The practice has been particularly well studied in West Africa. In Ghana, a recent survey (Boafo *et al*., 2019) showed that 42% of traditional poultry farmers give termites frequently and only 11% never give termites to their poultry. In a national survey in Burkina Faso (Sankara *et al*., 2018), 78% of the farmers said that they provide termites to their poultry, but the rate strongly varied among regions and provinces. This practice is also observed in other African regions (Munyuli Bin Mushambanyi and Balezi, 2002; Rutaisire, 2007). Termites are also occasionally given to fish. In Uganda, about 5% of fish farmers use termites as supplementary feed (Rutaisire, 2007). Termites are collected either directly by breaking termite mounds or by trapping them in containers filled with organic matter (Fig. 10.2). The harvesting methods vary with the region, the season and the termite genus (Boafo *et al*., 2019; Dao *et al*., 2020a). The trapping method has the advantage of not affecting termite populations and allows the collection of large amounts of termites. There are now efforts to improve the trapping efficiency and disseminate the technique among poultry farmers (Dao *et al*., 2020b).

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Fig. 10.1. Chickens feeding on live termites in Burkina Faso. Photo courtesy of CABI.

Fig. 10.2. Termite collection from a termite mound in Burkina Faso. Photo courtesy of CABI.

While less commonly used than termites, house fly larvae (*Musca domestica*) are also traditionally given to poultry and fish in smallholder farming systems in sub-Saharan Africa (Fig. 10.3). Data are mostly available for West Africa. In Benin and Burkina Faso, about 5–7% of farmers produce fly larvae to feed their poultry at least occasionally, and others collect them in decomposing wastes (Pomalégni *et al.*, 2017; Sanou *et al.*, 2018). Fly larvae are produced by exposing animal manure, agricultural or agro-industrial wastes to naturally occurring flies, and studies are presently being conducted to improve yields and production methods, including larval extraction and drying (Koné *et al.*, 2017; Pomalégni *et al.*, 2017; Ganda *et al.*, 2019). Other insects are occasionally given to poultry and fish, such as locusts and grasshoppers but mainly on an opportunistic basis during swarms (Kenis *et al.*, 2014).

Fig. 10.3. Dried maggots being fed to fish on a farm in Mali. Photo courtesy of CABI.

In the last two decades, new insect production systems have developed throughout the continent. While some focus on houseflies and crickets (Koné *et al.*, 2017; Irungu *et al.*, 2018), the vast majority of producers, in particular commercial companies, focus on black soldier fly larvae (BSFL, *Hermetia illucens*). All sizes of production systems are being developed, from small units adapted to African farming systems to large factories for industrial production. Research to develop BSFL production for individual farmers or micro-enterprises has mainly taken place in East Africa, where an increasing number of farmers are trained in the local production and utilization of BSFL. If conducted properly, BSFL production systems can be profitable and environmentally sustainable at both farm and country levels (Chia *et al*., 2019; Abro *et al*., 2020). There is, however, no data yet on BSFL adoption rates by farmers in Africa (Abro *et al*., 2020). While the objective of some BSFL producers is to produce insect protein for feed, others aim mainly at waste management or compost production from larval residues. However, it is generally considered that all three components of a BSFL system (protein and compost production and waste management) have to be included to make the systems profitable. For example, the largest insect producer in Africa, AgriProtein (http://agriprotein.com/ (accessed 3 November 2020)), uses food waste to produce BSFL proteins and oil for use in poultry, fish and pet feed, as well as soil conditioner. In Kenya, another company, Sanergy, uses BSFL to recycle faecal sludge from urban slums to proteins and compost (Nyakeri *et al*., 2019).

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11 Insect Production and Utilization of Insect Products in the USA and Canada

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Starting in the 1950s live insects (mostly crickets, mealworms and waxworms) were initially raised for sale as fishing bait in North America. As ownership of exotic pets became more popular, an industry centred around the raising and selling of live insects to feed these animals emerged, with most of the early producers also selling insects as recreational fishing bait.

In contrast to the long history of the sale of live insects the use of insects as ingredients in pet food and animal feed in North America is relatively new. This industry is growing in North America for several reasons including: (i) a desire to produce larger quantities of protein to feed the growing human population, and the animals that are used to feed them; (ii) a focus on production of more sustainable protein sources (e.g. based on land and water usage rates and greenhouse gas equivalents); and (iii) as a waste management tool to convert waste streams including those from food and feed waste and by-products as well as manure, into higher value protein (van Huis, 2016). However, applications of insect-derived ingredients in North America are currently quite limited and largely focused on exotic animals and other speciality applications. This is largely due to costs, availability, timing of regulatory approval for use in livestock feed applications, and the fact that North America is a significant producer of conventional low-cost animal feed ingredients.

Live 'feeder insect' producers currently consist of dozens of smaller speciality producers typically selling only a few species and a handful of large integrated producers selling a wide range of species. These include crickets (*Acheta domesticus* and *Gryllodes sigillatus*), yellow mealworms (*Tenebrio molitor*), superworms (*Zophobas morio*), waxworms (*Galleria mellonella*), black soldier fly larvae (BSFL) (*Hermetia illucens*), silkworms (*Bombyx mori*) and fruit flies (*Drosophila melanogaster and Drosophila hydei*). Some raise only a few species and buy species that they don't raise from other large commercial growers. This inter-company transfer likely facilitated the spread of the *A. domesticus* densovirus which devastated a large number of commercial cricket production facilities starting in 2009 (Szelei *et al*., 2011; Weissman *et al*., 2012). Producers then distribute these insects both directly to pet owners and through retail pet stores. Interstate transport of insects is regulated by the United States Department of Agriculture (USDA) because of concerns that escaped animals could establish new populations and become pests. Live insects for sale are generally exempt from Association of American Feed Control Officials (AAFCO) registration and labelling requirements.

The production of insects for human or animal consumption is similar in many regards to that of the live ‘feeder insect’ production system, but with an additional final processing step, converting live insects to a dried feed material. This may occur via heating or freezing then drying, and many different methods of drying insects are available (e.g. oven-based drying, microwaving, freeze drying) (IPIFF, 2019). The method chosen for processing may impact nutrient content and digestibility (Poelaert *et al*., 2018; Dobermann *et al*., 2019; Jensen *et al*., 2019), as well as microbiological risk (Fernandez-Cassi *et al*., 2019). Additional processing of insects is used to remove some portion of the lipid content, creating a protein-rich meal, and additional processing steps may be utilized to further refine these products (e.g. protein hydrolysates). Each insect-derived ingredient may thus have different nutrient profiles and nutrient bioavailability (Ozimek *et al*., 1985).

In North America there are currently a large number of small insect growers producing a variety of different species of insects for human consumption. In the USA and Canada, crickets and mealworms are the primary species grown for human food consumption. Aspire Food Group and Entomo Farms are currently among the largest producers of crickets for human consumption.

In regards to insect production for animal feed applications, there are currently only a small number of insect producers in North America, which is due in large part to the current regulatory status for insects in animal feed. Currently only BSFL (in the form of whole dried larvae and partially defatted high protein meal) have AAFCO approval for feeding to salmonid fish (trout and salmon) and for all species of poultry (AAFCO, 2020) (Figs 11.1 and 11.2). Thus, most producers have concentrated on BSFL production, and the first companies to commercialize this production in North America at scale include EnviroFlight, Enterra and EvoConversion Systems. Mealworm production is also beginning to grow in North America, with BetaHatch and others developing scalable rearing technologies. Finally, cricket production for animal feed is also growing, although as previously mentioned, most cricket production is focused on human food applications. While not livestock animal feed, the other approved use of dried insects in the USA is for inclusion into wild bird food. That use is limited to all life stages of insects commonly found in the wild in North America and used as food by wild birds although no specific species are mentioned. Due to the limited number of approved feed applications for insect-derived ingredients, and the fact that dried insects are currently not cost competitive with other more conventional protein sources used in animal feeds such as poultry meat and fish meal, there currently is very limited use of dried insects or insect meals in commercially produced pet food or animal feed. Estimated annual volume of production of dried insects for animal feed application is in the thousands to tens of thousands of tonnes per year. The rising cost of both meat meal and poultry meal and the limited availability of certain fish meals should increase the opportunity to use more insects in animal feeds and pet foods. At the same time, insect producers will need to refine and optimize their production processes to make costs more competitive with traditional feed ingredients and work with regulatory officials to expand the number of insect species approved for use in animal feed and the species to which they can be fed.

Fig. 11.1. Whole black soldier fly larvae. Photo courtesy of Enviroflight.

Fig. 11.2. Black soldier fly meal. Photo courtesy of Enviroflight.

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12 Insect Production and Utilization of Insect Products in Europe

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In Europe, as in other parts of the world, industrial-scale insect production has not been associated with animal feed until relatively recently. It was also not present in pet food, except when live food was required (mainly for reptiles or amphibians and to a lesser extent for ornamental fish and birds). For this reason, with the exception of beekeeping or the production of carmine pigment, the industrial production of insects has historically been dominated by their use as pest control agents and pollinators. However, over the past 10 years, some of these companies have diversified their activities towards the production of food and/or feed for farmed animals (including aquaculture) and pets. For this reason, most of the companies that are part of the emerging insect farming sector are relatively new. Current insect protein production in Europe is estimated at around only 3000 t/year, but the production of insect meal is expected to reach 1.2 million t in less than 10 years (IPIFF, 2019; Mancuso *et al*., 2019).

The main species of insects used for pet food and feed derive from those that had originally been bred in captivity for sale as live food or live baits for fishing. Some of these species are well-known pests (e.g. Calliphoridae, blow fly species), with high reproduction rates, and found to be amenable to artificial breeding. The situation changed radically in 2017, when the use of seven insect species, when reared on materials of vegetal origin, were authorized for use in aquaculture feed and this opened the market for insect producers. These species are black soldier fly (BSF; *Hermetia illucens*), common housefly (HF; *Musca domestica*), yellow mealworm (YM; *Tenebrio molitor*), lesser mealworm (LM; *Alphitobius diaperinus*), house cricket (HC; *Acheta domesticus*), banded cricket (BC; *Gryllodes sigillatus*) and field cricket (FC; *Gryllus assimilis*). However, the use of insects, and more specifically insect protein, is still quite limited in the European Union (EU) (Gasco *et al*., 2020; van Huis, 2020). For example, despite the fact that poultry and pigs naturally feed on insects in free range and organic systems, insect protein is not currently permitted in their feed. Fish, eggs, milk and derived products are not prohibited, but substrates containing meat or food scraps from restaurants or supermarkets cannot be used to rear insects. It is likely that without the COVID-19 crisis, the EU Commission would have approved the use of processed insect animal protein in the diets of monogastric animals by mid-2020. Today such limitations restrict market opportunities, and associations such as the International Platform of Insects for Food and Feed (IPIFF) are working to expand both the range of permitted

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rearing substrates and the feed applications to include poultry and pigs.

Currently, all of the seven authorized insect species, which are legally themselves considered as ‘farmed’ animals, are being used unevenly in the market for pet food (often as live food) and farmed animals (including aquaculture). The most promising species are BSF and YM and both appear as feeds of animal origin in the INRAE-CIRAD-AFZ[1] feed tables, see: https://www.feedtables.com (accessed 1 December 2020) (Macombe *et al.*, 2019; van Huis *et al.*, 2020). The pet food market is important for European companies because requirements are in line with current production volumes of the insect sector. Scientific evidence has supported marketing of dry insect-based pet foods in Europe over the past 5 years, and the number of products, particularly for dogs, is increasing (Kierończyk *et al.*, 2018; Paßlack and Zentek, 2018). These products have been introduced for specific veterinary aspects (e.g. as hypoallergenic or with anti-inflammatory and antioxidative capacities) and are marketed as more a sustainable alternative to animal products derived from industrial livestock production (Bosch *et al.*, 2016). The availability of insect-fed fish is currently limited by production capacity. Nevertheless, the French supermarket chain Auchan launched trout fed on insect meal in 2018 and in 2020, trout fed on insect meal enriched with algal oil, and fish trimmings (in collaboration with the BSF-rearing company Innovafeed). It is likely that this initiative will extend in the near future to include other species such as bream, bass and salmon, as well as shrimp and will be followed by others. In fact, Skretting, the largest producer of feed for farmed fish, signed an agreement in 2019 with the Dutch insect producer Protix, to produce salmon feed that incorporates BSF protein. Danish company BioMar has also evaluated feed formulations based on BSF or YM meals for trout, juvenile salmon and marine fish. The adoption of insect meal in European aquaculture is likely to spread rapidly as its price as a raw material becomes more competitive (Sogari *et al.*, 2019). Insect-derived fats are also interesting as a feed ingredient (Dabbou *et al.*, 2020) and, as they are not subject to restrictive legislation, may appear more extensively in the diets of monogastric animals than insect protein. Indeed, Coppens Diervoeding have been using BSF oil (in collaboration with Protix) in monogastric feeds since 2016, and Auchan recently announced production of organic poultry raised on insect-oil-enriched feed which eliminates the regular use of soya bean oil. Furthermore, feeding live larvae has been shown to have positive health effects on laying hens (Star *et al.*, 2020) and this is practised in countries such as the Netherlands for organic egg production. In 2020, WWF (World Wide Fund for Nature) and the British major supermarket chain Tesco, commissioned a roadmap for expanding insect protein production for use in animal feed.

The insect farming sector in Europe is represented mainly by small and medium-sized companies, with great dynamics in terms of the creation of new companies (Derrien and Boccuni, 2018). It is an emerging industry that draws from academically derived global innovation efforts, although companies typically develop ‘in house’ commercial production systems. Unlike other parts of the world, the EU exclusively uses closed systems (indoors), which via the control of environmental parameters (temperature, humidity, light) allow for more tightly controlled insect growth and development and hence product consistency. Great efforts are also being made in the development of advanced production techniques, including: (i) automation of production processes (to reduce labour costs); (ii) the optimization of breeding conditions; and (iii) the formulation of diets that maximize breeding reproductivity and feed conversion to insect biomass efficiencies. All of these characteristics are necessary to achieve the development of economically viable intensive industrial-scale insect production systems for the animal feed sector. In this sense, the European insect industry leads much of the innovation associated with mass production, with producers becoming established in the vast majority of European countries. Specifically, in terms of the number of business initiatives, several Central European countries stand out, which could be explained by their previous experience in the production of insects as live food. As such, Europe is one of the most active regions in scaling technologies to achieve intensive industrial insect production (Fig. 12.1). This is largely driven by the high demand for protein-rich feed in aquaculture and the availability of multiple types of high-quality organic wastes derived from the agri-food sector.

Fig. 12.1. Industrial-scale insect production. Photo courtesy of Enviroflight.

Private investors who see business opportunities at local, regional, national and international scale, together with government initiatives are helping to drive progress towards achieving economically viable and standardized production at scale. Innovation and investment, together with anticipated changes to legislation to permit insect protein in monogastric feeds, are driving the commercialization of insect products and will also facilitate the development of specific ‘premium’ production lines focused on certain nutritional aspects for pet food, terrestrial livestock and aquaculture. However, while insect protein is sometimes presented as a substitute for current protein sources, the technology advances necessary to grow insects at scale and viable cost is still in its infancy and it will be some time before the insect sector will be able to contribute significantly to addressing the global animal protein deficit. Nevertheless, it is clear that the industrial production, particularly of BSF and YM, from small farmers to large commercial-scale producers, could revolutionize the feed market in the coming years.

Note

[1] INRAE (Institut national de la recherche agronomique) is France's new National Research Institute for Agriculture, Food and Environment, created on 1 January 2020. It was formed by the merger of INRA (the National Institute for Agricultural Research) and IRSTEA (the National Research Institute of Science and Technology for the Environment and Agriculture). CIRAD is the French Agricultural Research Centre for International Development and AFZ the Association Française de Zootechnie (French association for animal production).

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13 Innovation Articles

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The science, state of the art, practicalities and human dimensions of insect farming are evolving globally at a rapid rate as you will have discovered in the other chapters of this book.

In the wake of this innovation drive, visionaries and entrepreneurs have emerged willing to stake their reputations and livelihoods on the back of this new farming system that has the potential to contribute to reforming global food systems.

In this section, ten entrepreneurs who have led the establishment of their companies and are vigorously leading their development, share their motivations and insights. Hear from those who now lead international well-established enterprises to those who are emerging from the start-up or pilot phase and continue to work towards that first significant grant, or angel investment, that will enable them to take the first step to scale up.

Thank you to all who gave their precious time for the interviews and the follow-up questions. On behalf of the researchers and practitioners around the world providing the evidence base for insect farming, thank you to all entrepreneurs for taking this work forwards, ensuring that all new actionable knowledge generated is utilized to the benefit of humanity and the planet.

Contact details for the companies and entrepreneurs featured are provided with each article for follow-up by readers.

Innovation Article: AgriProtein

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Fig. 13.1. David and Jason Drew – joint founders of AgriProtein.

As they grew up, brothers and co-founders of AgriProtein, David and Jason Drew, who used flies as bait when fishing as children, became increasingly aware of the challenges the world faces in feeding a growing population. In parallel, the Drews began to understand the challenge to our oceans coupled with fishermen's dependence on them, and the global challenge of growing mountains of food waste. They pledged to find a long-term sustainable solution using alternative sources of protein.

With this shared ambition, the brothers' journey formally began in 2008. Co-founder David explains: 'We wanted to produce insect meal for feed – profitably – from waste organic material whilst simultaneously reducing landfill and producing compost to help repair our fast-depleting soils. Farmed animals, fish and nearby waste gave our early work a framework of circularity from day one.'

From the beginning, the Drews focused on understanding the needs and drivers of the feed market. Their early connections with local farmers were invaluable in providing feedback on product performance, quality, and inclusion rates of different insect species in feed. It was over 5 years before the Drews were able to manufacture products at any commercial scale.

Over the 8 years that followed, the team developed the technology and processes behind the business of using discarded food waste to feed black soldier fly larvae, harvested to produce the alternative more sustainable and cost-effective feed to conventional fishmeal. The team kept going through some of the inevitable low points in the development years but were supported by collaboration with the University of Stellenbosch, as well as focusing on their 'vision it, build it' attitude which ensured the company continued to move forward.

One of the biggest challenges faced by AgriProtein during the innovation 'to market' phase was animal feed legislation inhibiting innovative production. Their business and technologies focused on repurposing organic waste streams to make high quality insect meal – 'simply follows nature's lead' – reflects David, as flies have for millions of years laid their eggs to produce larvae on all kinds of organic waste, before they naturally and safely re-enter the wild feed chain.

'Yet modern farmed animal feed legislation continuously lags behind innovation,' explains David, and continues, 'So as pioneers with a clear duty of care to scientifically prove the safety of our processes, we have worked with universities around the world to achieve the data to support legislative change. Some regional legislative differences on substrates and rearing procedures remain that are continuing to hinder global "meshed" market acceleration.'

In 2015, AgriProtein opened its first 9000 m^2 full-scale facility in Cape Town, South Africa, successfully scaling up production further and subsequently allocating international licences for use of its technology in Asia, Australasia and the Middle East. It now also has fly farm projects across the globe in the USA, South Africa, Korea and Saudi Arabia, following a partnership with Austrian engineers Christof Industries in 2017, rolling out its fly factory blueprint on a turnkey basis across the world.

AgriProtein has received significant amounts of investment since its inception, including US$18 million from undisclosed investors and grants for its research from the Bill and Melinda Gates Foundation. As the founding team had successfully started and exited a few businesses, seed capital was not a problem. In 2018, its parent company, the Insect Technology Group, raised US$105 million to fund the company's expansion into Europe through acquisition and joint ventures with other related businesses. More recently AgriProtein announced the launch of a new US joint venture with PreZero to form an operating entity for nutrient recycling processes using circular economy principles in the USA.

What started as a wild idea in a tractor shed in South Africa is now a multinational company, a key player in the insect-as-feed industry, with over 200 employees in 11 countries, ranging from Hong Kong to the UK and Singapore to South Africa. The company has a global target of building 100 fly farms by 2024 and 200 by 2027, contributing to the global scale up.

'Currently insects as feed are still nascent, production is niche,' says David. 'However, over time further industrial capital will start to flow, replacing today's venture capital to fund site replications and start to really grow the percentage share of the only alternative animal protein feed.'

David Drew concludes: 'We want to have tens of factories, diverting hundreds of thousands of tonnes of organics from landfill, manufacturing hundreds of tonnes of meal and oil each day at point of need. We want to have better protected oceans, better fed farmed fish and animals, and better, more naturally reared food on our children's tables through truly sustainable green tech advancement.'

The Drews, AgriProtein and its associated companies are proud to be part of delivering that future vision, including documenting *The Story of the Fly: and How It Could Save the World* (Drew and Joseph, 2014), and providing an updated edition written by Jason Drew published in 2021.

At the time of going to press, ITG/AgriProtein was exiting a period of corporate receivership.

Innovation Article: Agroloop

AGROLOOP

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Fig. 13.2. Agroloop's research and development (R&D) facility and (inset) Rajmond Percze, Managing Director, and István Sándor Nagy, Chief Executive Officer (CEO).

The 'friendship team' that founded and continue to develop the company Agroloop became aware of the potential of black soldier flies (BSF) as an alternative protein and fat source when reading articles about their potential in 2017.

'The revelation of this potential built on our increased awareness of the major sustainability issues confronting agriculture and the globe,' says Rajmond Percze, Managing Director of Agroloop. 'The erosion of agricultural land and low sustainability in the current food chain, combined with the promising food conversion ratio (FCR) being described, convinced us to investigate further both the biological and business potential of BSF.'

The team, consisting of biologists and mechanical engineers, invested significant time in building a range of plans resulting in a conviction that they could create a profitable business based on this emerging 'green technology'. In common with most forms of innovation, the team encountered attitudes in Hungary and elsewhere that Rajmond describes as 'reluctant' – but bolstered by new research and industry-based information and personal experiences in Wageningen, Holland where interest in the use of insects for both food and feed were accelerating, the team persevered and Agroloop was born in 2017.

'Based on our own conviction plus the support of friends and business connections who heard our story,' continues Rajmond, 'we applied for a number of grants and awards across a range of communities and accelerators such as the Climate-KIC. Success here allowed us to believe that we had the potential to grow into something great.'

The award of €10,000 from the Climate-KIC, plus recognition from the European Commission (EC) in the form of two 'Seal of Excellence' awards for their project proposal 'Feed protein production from food waste by industrial-scale BSF farming', evaluated as high quality by an international panel of experts, provided a significant boost to morale and reputation for the group. The slow pace of development in the regulatory environment required – and still requires – a great deal of perseverance, potentially impacting on resolve as well as the innovators' mental and social health.

'The Climate KIC and Katana Accelerator programmes provided us with funds of course, but more importantly provided verification that our plans were and are viable,' adds Rajmond. He continues:

'These programmes opened up conversations and connections with different stakeholders addressing the same core challenge – agricultural unsustainability and the increasing demand for food and feed. These interactions focused our thinking and our actions, spending time in Hungary in educating the players across the value chain as well as investors whilst we saved funds in order to develop our MVP – minimum viable product.'

Agroloop is now in 'the seed stage' having secured their first and current investor. For many investors either the 'ticket size' or lack of market readiness was not ideal for them, Rajmond and colleagues encountering many culturally-based negative perceptions based on anticipated end-consumer reaction.

Working with insects (BSF), fed on a blended substrate from food waste and from which Agroloop makes their products – protein, oil and frass – is a 'big idea' for many on the outside of this emerging industry to take in, but it is changing. With more studies published and validation of insect-derived products emerging particularly over the last 2 years, coupled with the growing clamour for increased sustainability in both the feed and the food chains, Rajmond and the growing team perceive they are on increasingly solid ground.

Rajmond states:

'Market and industry news and reports are supporting the vision and potential we have.

The largest animal feed producers need not only to drive research but also adopt these ingredients to support their move to sustainability, and this has begun to happen in 2020 – a real kick-start for our company.'

While 2020 and the COVID-19 epidemic has slowed progress, a small-scale research and development (R&D) facility is now in operation producing 2 t/month of live larvae, with plans in place for the first commercial-scale factory to start production in 2022 in Hungary. Availability of the preferred residue stream with which the company creates its blended and consistent substrate on which to grow its BSF larvae, the familiarity of their mother tongue plus the current weak competition in their home country of Hungary make this the ideal choice. Recent funding from the Hungarian Government to support the development of companies producing protein locally has been a bonus. By 2025 Agroloop aim to have at least another large-scale facility located somewhere in Central Europe, not necessarily in Hungary.

Agroloop's assessment of where the 'insects as feed' market will be in 5 years' time is that it will be a commodity, not an exotic product in the feed additive market as all stakeholders become familiar with insects, not as a subject of disgust, but as a valuable and indispensable part of the feed chain. The major hold-up, in common with many sectors, is the regulatory environment, with agreement at European Union (EU) level to allow insect-based products into poultry feed being pivotal to driving compound feed production at scale.

Rajmond adds: 'Regarding the acceptance rate for the human consumption of insects, we do not believe that in 5 years' time insects will be playing a huge role in the Western diet, mainly due to the lack of an established cultural base, hence our ongoing focus on feed.'

Rajmond and his Agroloop colleagues believe that it was the story that they kept telling themselves and everyone who would take the time to listen that is the foundation of their progress and success.

'Our story that once was an unclear dream,' concludes Rajmond, 'has evolved into a real-world problem solution, progressing to successful manufacture of our products based on circular economy principles. Our success will contribute to helping the human race tackle the protein demand issue on a global scale – sustainably.'

Innovation Article: Beta Bugs

Beta Bugs | Roslin Innovation Centre, Easter Bush Campus, Edinburgh, EH25 9RG, Scotland, UK | Thomas Farrugia – Founder and CEO | info@betabugs.uk

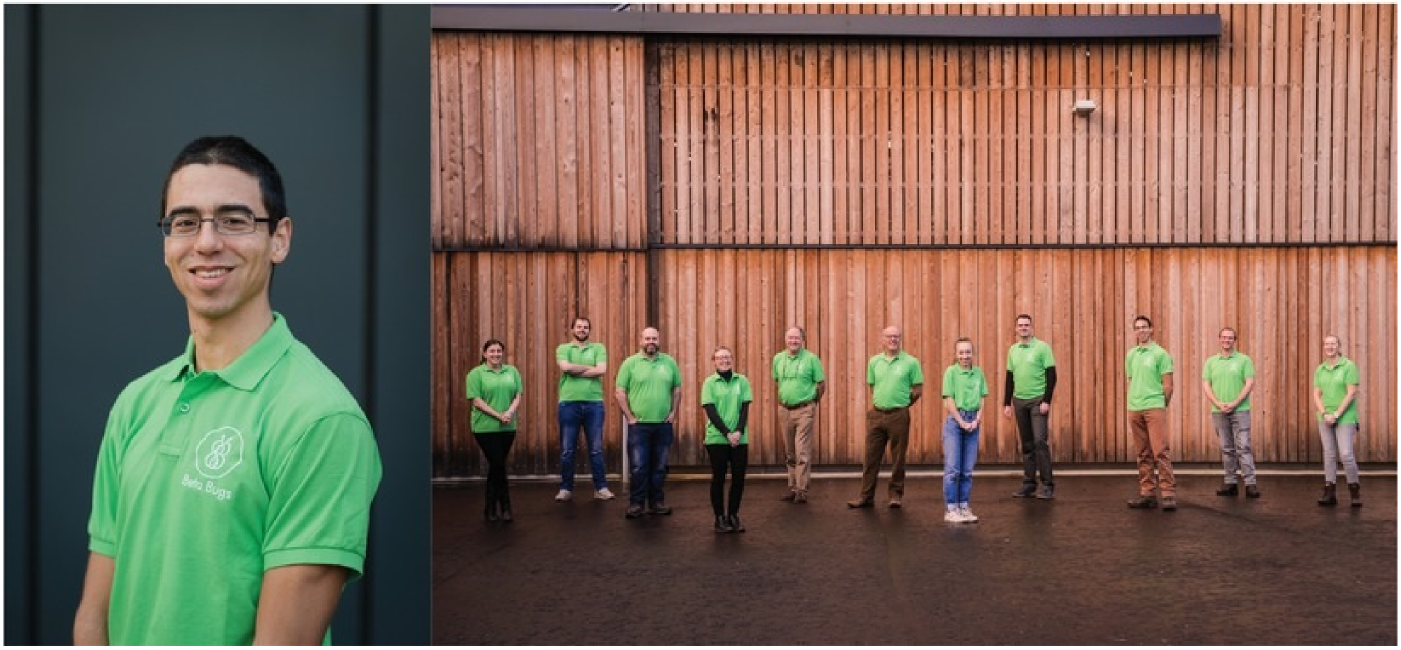

Fig. 13.3. Thomas Farrugia, founder and CEO of Beta Bugs, with his team.

When Thomas Farrugia first tasted ‘bugs’ in Belgium during a 3-month placement, he was probably not aware that this experience was the start of his dedication to building a company to produce quality insect protein. ‘It was actually a few years’ later,’ states Farrugia, ‘that I first read about and began to understand the potential of insects.’ Five years later, having learnt how environmentally friendly insect-based products are, Thomas leads the company Beta Bugs having attracted significant funding and support from governments, projects and investors.

Originally from Malta, where he gained his BSc in Chemistry at the university in 2012, Farrugia followed that with a Masters at Imperial College London and his PhD in Chemistry at the University of Bristol before making the switch. It was his involvement with investors at Deep Science Ventures in 2017, battling for funding for scalable innovations that enabled him to set up Beta Bugs later that year, supported by the £50,000 he secured in return for equity.

‘Insect farming is capital intensive,’ explains Farrugia. He continues: ‘It requires significant investment for premises, hardware and software – so I did not go down that route. My idea focused on where we could make the biggest difference in the value chain – high-performance insect breeds that deliver consistent quality for the insect farmer.’

From modest accommodation and a simple insectary, first in Bristol then at Rothamsted, Hertfordshire, Beta Bugs is now established at the Roslin Innovation Centre near Edinburgh, where Beta Bugs and Farrugia have access to world-class knowledge and contacts that have supported development.

‘Our move to Scotland has been extremely positive,’ says Farrugia. He explains: ‘One major advantage of being here is the number of organizations with related agendas, such as Zero Waste Scotland, encouraging the better use of waste streams and creating opportunities to work together collaboratively. Scotland is also extremely good at taking care of small companies – there is a good ecosystem for start-ups and investors.'

Contacts at Roslin and at the Knowledge Transfer Network (KTN) encouraged his successful application for the Royal Society of Edinburgh's Unlocking Ambition Enterprise Fellowship, securing £45,000 in funding from Scottish Government. This led to further funding via an SME (small and medium-sized enterprise) Instrument Phase 1 grant of €50,000 from the European Commission, followed by Beta Bugs leading on a £500,000 Innovate UK project with the Roslin Institute, world leader in animal genetics. Over the last 18 months, the company has secured £133,000 of private investment, along with £1.2 million in grant funding, including £100,000 from The Scottish Government's Unlocking Ambition programme and £84,000 from the Pivotal Enterprise Resilience Fund to help the company continue to grow its operations during COVID-19 lockdowns.

Farrugia has experienced the stress and intensity that setting up your own innovative and breakthrough company can entail and advises to be aware of the potential negative impacts that can arise if these are not addressed. He says: 'Negative feedback can be useful, but in the end, you are closest to the furnace, and must make the decision as to whether you pursue an opportunity or not. This is especially pertinent when pursuing something which has not yet been done before, and when critique and preconceptions concerning 'genetic engineering' and the possible escape and impact on native species of 'super flies' are voiced regularly.'

The response from Farrugia has been to focus ever more intently on creating the evidence and practical information to show that using a combination of biotechniques and a state-of-the-art genetic breeding programme, strains can be created with performance that far outstrips natural strains.

'Insect breeds have not been fully optimized yet,' explains Farrugia. He continues: 'Better bugs will be one of the crops of the future with huge potential to drive a sustainable bioeconomy. Our continuing challenge is to optimize insects for industrial use – make them easier to farm and become more efficient sources of protein and other products. The aim is to double productivity – and thus profits for farmers – via growth rate, protein content, fat composition and temperature tolerance.'

In addition to the markets for livestock and fish feed, Farrugia recognizes future potential in the fuel and biomaterials sectors, as well as from retailers looking to improve their credentials as sustainable suppliers of healthy nutrition by increasingly providing insect-fed produce such as chicken and fish for their customers.

The ambition for Beta Bugs in 5 years' time is to be a world-leading genetics company, supporting the insect farming sector to produce consistent quality protein via their super breed of black soldier fly, helping to feed and fuel the world. The company's recent opening of its new dedicated insect breeding facility at the Easter Bush Campus, within the Science Zone in Midlothian in January 2021, is definitely a step in the right direction. With invaluable support and advice from various organizations including Business Gateway Midlothian, the new facility will see the creation of five new roles within Farrugia's growing team and help the company to continue to carve a niche in the UK and international genetic insect market.

Farrugia’s advice to anyone already on their entrepreneurial journey is clear. ‘If you have an idea that is already tested and implemented at least to a degree, stick with it – stress test it as much as possible in collaboration with others, but don’t be diverted from your ultimate goal.’

Innovation Article: Beta Hatch

Beta Hatch, Seattle, Washington, USA | info@betahatch.com
Established in 2015 by founder and CEO Virginia Emery, a PhD entomologist from the University of California, Berkeley, Beta Hatch grows insects to provide sustainable protein for animal feed.

Fig. 13.4. Virginia Emery, founder and CEO of Beta Hatch. Photo ©Kurt Schlosser GeekWire.

As an entomologist, conservationist and biologist, Emery wanted to find a way to include insects in the food system rather than spend time trying to kill them by developing pesticides. As they form the basis of most food chains, the vision was to see insects as a resource within the food system offering nutrients to advantage human and animal nutrition.

Emery was also driven by the challenges of climate change and food production. Washington has a huge agriculture industry that can benefit as climate change makes growing conditions in the Pacific Northwest more favourable, particularly relative to drought-stressed agriculture in other areas such as California. Washington offers milder weather, inexpensive electricity, and space available for building indoor farms.

Emery says: ‘One of my biggest personal challenges has been in adapting my communication style. Having trained as a scientist and then becoming an entrepreneur, I have had to adapt the way in which I communicate about the business and speak to investors. Entrepreneurs need to speak with more certainty and less ambiguity than scientists, even when there are unknowns.’

‘The world needs to produce 70% more food by 2050,’ Emery explains, ‘but per-capita agricultural land has decreased. We need more human food, and more feed for the animals we eat. Among the costliest inputs to farming are protein-rich feed to grow meat for humans, and fertilizer to grow produce, complicated by the fact that up to 60% of feed and food is wasted. Using insects can help address all these problems.’

Beta Hatch, which currently operates out of a facility in Cashmere, Washington state, has developed an insect-rearing technology that converts mealworms and their waste into proteins, oils and nutrients for the agricultural sector, combining proprietary processes and superior genetic stock. Beta Hatch is developing the tools needed to grow insects on an industrial scale to disrupt plant and animal nutrition, while trying to close the supply chain loop and move towards more regenerative agriculture.

For its feedstock for the mealworms, the company uses grain and fruit-based organic waste products from local processors – distiller grains and apple/fruit waste – some of which travel fewer than 5 miles. Mealworms require minimal water and grow at up to 500 times the acreage yield of soya. The selective breeding programme from its hatchery in Washington produces eggs which are then reared at grower-owned and operated ‘insect ranches’. The company’s scientific approach to scaling insect production using this hub-and-spoke operational system, the first such farm in the USA, has brought it international recognition.

‘Our core aim is to be cost-competitive with fishmeal and provide a feed source that is potentially healthier for livestock as well as being more sustainable,’ says Emery. ‘The team has already engineered several innovative solutions to increase insect growth and mechanical processing efficiencies that deliver a competitive edge in this space.’

Currently employing 18 people, the company plans to recruit up to 30 new staff members in operations, engineering and R&D in anticipation of their flagship 30,000 ft^2 (2787 m^2) semi-automated facility in Cashmere which will be completed in 2021. The building will be partially powered by waste heat from a neighbouring data centre to reduce electrical needs.

Beta Hatch recently completed detailing the genome of the yellow mealworm which is published as an open-source article in the *Journal of Insects as Food and Feed* (Eriksson *et al.*, 2020). This public genome is a valuable resource for furthering research on the mealworm and other commercially relevant insect species which, with other new research, could accelerate the growth of the whole industry and stimulate yet further research studies by labs in both the private sector and the public sector.

Initially ‘bootstrapped’ by its founder, the company has attracted private investors together with state and federal funding. The Washington Government’s Clean Energy Fund has provided grants to help repurpose waste heat for its new facility, with further funding through the federal Small Business Innovation and Research (SBIR) grant program for R&D. Initial seed funding was used to establish a pilot facility producing about 200 lb (90.7 kg) of mealworms and 400 lb (181.4 kg) of frass each week. Its target markets for its dried mealworms are aquaculture, pet food and for poultry feed, while the frass produced is a natural organic plant fertilizer for both indoor and outdoor plants, which will be available to consumers in 2021.

As of December 2020, Beta Hatch has raised a total of $18.6 million in combined equity and non-dilutive funding, including its seed round in 2018 and Series A financing in 2020. Funding by its investors, including Cavallo Ventures, AccelR8, Brighton Jones Investment Partners and Innova Memphis, allows the company to continue to innovate its technology as well as move its entire operation to its new purpose-built site.

About the future of Beta Hatch, Emery says: ‘Our company is currently focused on the mealworm, but our core technology is the platform we have developed to mass produce protein and lipids. While we are focused today on animal feed, there are innumerable opportunities, particularly in pharma, to leverage our platform for incredible growth.’

Emery also recognizes that while her company’s focus has been on animal feed, as consumers are wanting to know more about the origin of their food, its rearing, harvesting and processing, these trends could drive further market adoption of insect protein for human consumption. For now, however, the company is focused on making an impact on food by nourishing the animals that we eat, and those with which we share our homes.

Emery concludes: ‘Beta Hatch’s current ambition is to expand nationally. Once our new facility is up and running, it will directly produce a tonne a day of mealworms but be able to support thousands of tonnes of production as a hatchery, making us the largest producer of mealworms for animal feed in North America.’

Innovation Article: Entec Nutrition

entec nutrition

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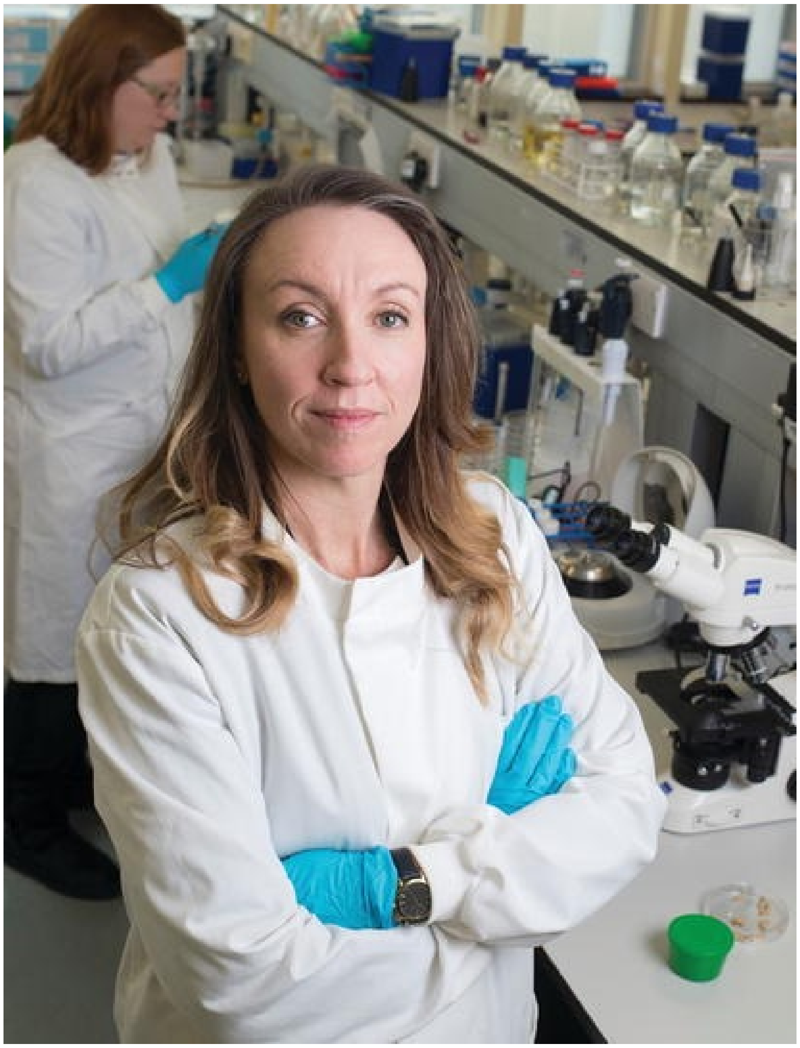

Fig. 13.5. Dr Olivia Champion, co-founder of Entec Nutrition.

As a microbiologist with an interest in bacteria, Dr Olivia Champion, co-founder of Entec Nutrition, was interested in insects and their natural resistance to bacteria found in the environment.

‘Through working with *Galleria mellonella* in my academic research,’ explains Dr Champion, ‘I realized the potential for insects in the agri-tech sector. The climate crisis and the fact that insects are a sustainable source of high-quality feed ingredients, with added value, was what initially attracted me to setting up Entec Nutrition.’

Having already established a university spin-out company with a focus on insects for research, Champion was experienced in the steps needed to drive forward and commercialize an idea. She had previously attended the Innovate UK-funded iCURe (Innovation to commercialisation of university research) training programme run by SETsquared, a collaboration of UK universities, to commercialize academic innovation, as well as boot camps where entrepreneurs could pitch their ideas and business plans against stiff competition.

‘Meeting like-minded entrepreneurs at these competitive events was both challenging and inspiring,’ states Champion, ‘as well as creating a network of contacts that continue to keep in touch via WhatsApp groups.’

Soon after Entec Nutrition was founded in late 2018, seed funding was secured which enabled the company to carry out the R&D that has underpinned their patent applications, the funder providing both challenge and support in regular meetings which was of great value. Such support enabled the company to win an agri-tech grant from the EU Regional Development Fund, and significantly Innovate UK funding of £250,000 from the transforming food production scheme. The aim is to lower the cost of production and support the reduction of the carbon footprint of the UK's animal feed industry.

'Securing the Innovate UK grant in autumn 2020 won by partnering with larger organizations such as Campden BRI and building a competitive consortium is key to our development,' continues Champion. 'It has enabled us to join the Agri Tech hub at the University of Exeter Penryn Campus in Cornwall, providing connections with others working in the field of edible insects as well as driving forwards our R&D.'

The hub also provided Champion with access to talent, as here she found her first employee in 2019, someone already experienced in research on edible insects. One of the hardest aspects of growing a business is finding and keeping the right talent, reflects Champion, and as the company grows this may become an inhibiting factor. However, being part of the EU-funded Marie Curie project Insect Doctors, training young researchers in aspects of insect rearing and production, may provide Entec Nutrition with a source of talent, in spite of employment hurdles due to Brexit.

There is no doubt that the combined effects of the COVID-19 pandemic coupled with Brexit have been a significant challenge for Entec Nutrition. Research activities have been delayed due to working restrictions such as the requirement for a COVID test prior to entering the laboratory, rules around access and inability to provide training due to proximity restrictions.

'We have also experienced supply chain issues,' Champion explains further, 'including delays in receiving materials required for R&D. In addition, home schooling three children for me personally during the pandemic when the schools have closed has been a challenge!'

'One factor that has kept me motivated to continue progressing is having a really focused, hard-working team around me who all believe in what we are doing,' confirms Champion. 'It's a pleasure to work with such a great team – we push each other forwards in our shared ambitions for Entec Nutrition.'

However, despite these significant personal and business challenges, Entec Nutrition led by Champion, filed its first patent application in January 2021. In addition, in late 2020, the company started an in-depth customer discovery phase to understand the market and began a pilot study with a large industry customer.

Champion is clear that there are three factors currently hindering market acceleration: (i) legislation, which currently does not allow insects in poultry feed; (ii) the comparative higher cost of insect protein compared with other sources; and (iii) the scale of insect production. Demand for protein for animal feed far outstrips supply, from even the largest of the established industrial insect producers. Awareness around the potential for insects for food and feed from a sustainability perspective is increasing the call for change from outside as well as inside the industry.

‘To overcome these issues and help meet demand, Entec Nutrition is focusing on the added value factors associated with insect ingredients and developing technology, expertise and know how in this area – the topics of our evolving patent applications,’ Champion continues. ‘The industry is in its infancy, but its potential is clear, so technology and policy developments will emerge to address these issues in the coming years.’

The future vision for Entec Nutrition itself is also clear. Champion says: ‘In 5 years’ time, my aim is for Entec Nutrition to have filed at least three patents around the R&D we are currently undertaking and plan to develop. We will license our technology, provide expertise and know-how in this area and, in addition, we will have developed, and be selling, our own Entec Nutrition insect-based products.’

Innovation Article: Entocycle

ENTOCYCLE

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Fig. 13.6. Keiran Whitaker, founder and CEO of Entocycle. Photo courtesy of Naomi Wood.

Founded in 2016 by Keiran Whitaker, Entocycle converts food waste into protein for animal feed using insects, combining well-established farming methodology with high-tech engineering to process waste into high value protein for animal feed.

After Whitaker completed his Masters in environmental design and sustainable urban spaces at the University of Manchester, UK, he spent 5 years travelling, witnessing first hand the damage that intensive farming was having on oceans and rainforests. Keiran decided it was time to act himself. Driven by his passion to protect our planet and particularly the stressed local ecosystems he has witnessed, Keiran left his job, and set out on a mission ‘to develop a more efficient and sustainable way to feed the world’.

Initial independent work began in 2014 in Brazil where Whitaker set up a self-funded pilot facility using BSF, a hardy native species, once taken into battle by Native American warriors, and importantly where the cost of living is low.

‘As the larvae of BSF survive for several months without food, legend has it that warriors carried them with them in a pouch, and if they became injured, they used the larvae to clean their wounds,’ adds Whitaker.

In 2016 he moved back to the UK, joining the accelerator program MassChallenge in London, securing funding here, together with a first grant from Innovate UK which enabled him to set up Entocycle later that year and focus on producing insect-based protein feed using BSF larvae. As a non-disease, non-pest fly species, able to eat most waste and quick to breed, BSF is a sustainable protein replacement source for fish and soya meal.

‘BSF is the only fly species on the list of insects currently allowed by the EU for use in animal feed,’ explains Keiran, ‘and its particular life cycle with the larvae created being a “turbo charged protein bar” due to its massive consumption of feed as opposed to the adult stage, makes it ideal for this purpose.’

In 2017, the company received its first serious funding, won against significant competition, from the American seed money start-up accelerator, Ycombinator, with Keiran spending time in California while still running the UK company.

‘Being one of the only solo UK founders out of the 40,000 applicants was a significant achievement and the funding received enabled us to grow and develop our UK business,’ states Whitaker. It enabled the design and build of the company’s two facilities in London, driving the company’s R&D and development of innovative technologies to help organizations produce insect protein successfully, rather than Entocycle focusing primarily on producing protein itself. Hiring of staff occurred in parallel, with a focus initially on hiring those with business development skills.

With Whitaker’s mindset that ‘engineers of today are the farmers of tomorrow’, Entocycle now has an expanding team of highly skilled engineers, using precision farming techniques to maximize protein yields from BSF larvae, to meet the needs of their business-to-business customers. Financial support from the supermarket group, Tesco, has enabled further scale-up operations, supported by their encouragement to its fish suppliers to buy insect-based feed from Entocycle, while also planning to supply waste as food for the BSF larvae.

The single biggest challenge faced by Entocycle and the insect industry overall has been and remains legislation.

‘Insects are currently classed as farmed animals and can only be fed on approved feed sources,’ continues Keiran. ‘If regulation in the home market were to change to broaden feed sources by declassifying insects as farmed animals, this would unlock insects’ full circular economy potential, helping the UK to be perfectly poised to become a serious global player.’

The UK’s large agricultural base and significant salmon farming sector, its record of being the highest producer of food waste, and the growing trend of consumers willing to pay at least a little more for food produced sustainably, combine to increase the viability of insect farming.

Whitaker continues: ‘Now that we have left the EU, our farmers will struggle, and we need to provide for them innovative opportunities and solutions – such as insect farming – and in the process manage our huge volumes of food waste and reduce the UK’s reliance on imports.’

Growth of the global insect industry was accelerated everywhere in 2017 by changes to European legislation allowing insects as a feed ingredient into aquaculture. Progress has accelerated further in certain European countries – Denmark, France and Germany – by the introduction of national long-term protein plans which provide considerable funding and support for start-ups and growing enterprises focused on alternative protein development, providing a head start over other countries. The UK currently does not have such a plan but did for the first time, as part of UKRI's (UK Research and Innovation) Transforming Food Production Challenge, issue a call for proposals around insect farming.

Entocycle led the creation of a consortium, working with members of the UK's Insect Biomass Conversion Task & Finish Group which had called on government to recognize insect protein as a sustainable and healthy source of protein. The group won the grant of £10 million, and, led by Entocycle, will build the first industrial-scale insect farm in the UK located outside London.

'The Government's £10 million investment in the project marks a commitment for the UK to become a leader in sustainable food production systems,' says Whitaker. He continues: 'We plan to breed up to 5 million BSF larvae as protein for animal feed, and the frass will be sold to the horticultural industry as fertilizer. The new facility will be able to process up to 33,000 t of food waste a year.'

Having proven its technology can deliver scaled-up volumes, Entocycle will further establish itself as the leading UK provider, and plans to have between one and three further facilities up and running in the next 5 years, in addition to two to three licensing partnerships to supply the equipment necessary for full factory development. In 5 years' time, Entocycle believes the insects as feed market will continue to grow and be supported by high-end companies as they increasingly consider the environmental angle within their supply chains.

'With this recent support from the UK Government and hopefully changes in legislation to follow, we can continue to develop the UK insect protein market, becoming a global player whilst protecting our planet in the process,' says Whitaker, concluding 'whilst I remain a global pessimist, I am also a local optimist.'

Innovation Article: Future Green Solutions (FGS)

Future Green Solutions | Perth, WA, Australia | www.futuregreensolutions.com.au
Luke Wheat, Managing Director | admin@futuregreensolutions.com.au

Fig. 13.7. Luke Wheat, Managing Director/Founder, Future Green Solutions (FGS).

With a passion for conservation and sustainability, the founder of Future Green Solutions (FGS) Luke Wheat was drawn to the idea of insect farming as a way of confronting multiple current world issues with one simple solution. He founded FGS in 2008 to farm BSF to address the demand for sustainable protein and oil feed inputs for the aquaculture and livestock sectors, improve agricultural soil health and productivity, as well as management of agricultural and food waste. It currently has 13 employees and supplies the home market from its plant in Perth, Western Australia.

Wheat says: ‘Having worked across industry, conservation and sustainability, the divide between the scale, budget and longevity of projects was evident to me. Sustainability and conservation projects were often localized in scope, relied heavily on philanthropy, and would often fail to continue for more than a few years. Insect farming provided an opportunity to monetize numerous sustainability outcomes and ultimately allow these outcomes to become self-perpetuating to achieve industrial-scale outcomes.’

Wheat and his team focused on BSF as this species was introduced to Australia as a non-pest species in the 1970s and which addresses a number of environmental outcomes in one process, including the reduction of waste in landfill and the associated greenhouse gases produced. Four years of independent work, refining the process of farming BSF and conducting trials to improve production was required before other stakeholders became heavily involved with the project.

Partners have included the University of Western Australia, Perth NRM, Food Future WA and GEA one of the world’s largest suppliers of food processing technologies, which has supported FGS with expertise since 2017, plus a ‘separating decanter’ which has proven to be key to the company’s refining process. Additionally, Luke remarks, FGS has been lucky enough to be surrounded by numerous support networks, both personal and professional, which have acted as excellent sounding boards as the business has matured.

‘Collaborative research with industry partners has been imperative in establishing market confidence and accelerating the industry and our project,’ Wheat explains. ‘Working alongside research, government and industry institutions, has opened up opportunities and enabled us to become involved with testing BSF technology as a waste management process to produce frass fertilizer and soil improver products.’

A considerable period of self-funded research was finally rewarded by significant funding from the Australian Federal Government and Research Development Corporations, which together with loans and investment have accelerated the company’s growth. In 2018, FGS became involved with research into the mechanized production of insect proteins for aquaculture feedstock and in December 2020 a consortium, with FGS as the commercial partner, was awarded a A$2.5 million Commonwealth Grant to develop solutions for agricultural waste disposal using BSF.

Reflecting on the early years of R&D, Wheat says that finance was the most restrictive obstacle the company had to overcome to progress during the ‘to market’ phase, especially given the high capital intensity of lab and pilot-scale equipment required. In addition, early uncertainty surrounding legislative requirements presented some confidence issues around eligible substrates and markets – although these issues are now largely resolved.

Despite these challenges, Wheat has remained undeterred and continues to be driven by his passion for sustainability stating that ‘Our underlying passion for sustainability has and always will be our guiding flame.’

The company currently has 13 employees and is now involved in a A$4.2 million research project focused on improving the creation of high-quality fertilizers and soil improvers from agricultural waste. Funded by the Australian Department of Agriculture, partners include Australia Pork Limited as the lead, the Australian Meat Processing Corporation, the Fisheries Research & Development Corporation and the University of Western Australia.

Having now secured significant business investment alongside the research projects, FGS is now well on the way to opening its first commercial facility within the next 18 months, with plans to process 10–20 t waste/day and producing 1 t protein meal/day, with more plants to follow.

When asked about where he sees the insects as feed market in 5 years’ time, Wheat responds: ‘I believe that in that time scale, insect proteins will have moved away from their current “novel” branding and positioning to become a serious and stable protein source.’

Innovation Article: LIVIN farms

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Fig. 13.8. Katharina Unger (CEO LIVIN farms) and team at Lidl. Left to right: Thomas Riel (Chief Technical Officer LIVIN farms), Katharina Unger, Nenad Zivojinovic (Lidl), Juree Rattanatip (LIVIN farms).

Katharina Unger, industrial designer, and founder of LIVIN farms, set out on a mission to ‘feed the world whilst saving the planet’ when she registered the company in 2015. Based in Austria and Hong Kong, LIVIN farms has two inter-twined areas of activity: (i) education for households and schools to increase understanding and behaviour change regarding insects by rearing mealworms on household food waste; and (ii) industrial technology mass rearing solutions for businesses.

‘In Hong Kong, I worked alongside the fish market with its abundance of available food in such a small space and that inspired me to look into the global food system and how it works,’ explains Unger. ‘Enquiries led me to looking at insects and their potential for producing protein from food waste.’

After finishing her Masters, Unger went to the USA on a Fulbright scholarship, just at the time when interest in insect farming began to expand, boosted by the 2013 United Nations (UN) Report (van Huis *et al*., 2013) recommending consideration of this innovative field. Her American location allowed her to work with a range of people already in the field, travelling to Hawaii to help start up a BSF-rearing facility, then with MIT (Massachusetts Institute of Technology) to Africa, and then back to Asia where her idea had had its genesis.

‘It was in Malaysia that I secured my first client enabling the manufacture of the original version of my home mealworm-rearing device – the Hive – which were manufactured in China,’ Unger continues. ‘Our first investor followed – the China-based HAX accelerator programme – enabling the set-up of LIVIN farms with my partner Julia Kaisinger, the re-design of the Hive Explorer and a kick-starter campaign in 2015 through which 800 Hive devices were purchased.’

Unger cites several challenges that delayed further development in those early days. The industry was in its nascent phase, and despite a lot of interest from many quarters the amount of research available was limited, resulting in restricted investment opportunities despite the acknowledged potential. Unger considers they were very lucky to secure the investment they did.

‘It is still not easy to get funding for this industry,’ she continues, ‘it is an ongoing challenge although it is easier than before. You have to speak to many people in order to make your case and achieve success. But this is the same for all entrepreneurs – not solely in this sector.’

LIVIN farms has been successful in securing further seed funding plus support from the Austrian Research Promotion Agency – FFG – and in August 2020 became one of two Austrian companies to be awarded a grant by the European Innovation Council (EIC) as part of the European Green Deal programme, raising a total of €2.5 million. Unger puts her success down to ‘talking with stakeholders early and directly to understand clearly what they need to provide workable and sustainable solutions’.

Focus remains on mealworm – a ‘gateway insect’ – for the education side of the business. Due to its neutral, nutty taste, the ability to grow large amounts in a small space – and the fact it is already eaten around the world – it is ideal for home use. The LIVIN farm’s climate-controlled ‘Hive Explorer’ allows the insects to work their way down the Hive, from the top tray to the bottom. The by-product produced is an ideal nutrient for plants and as the mealworms are fed on plant-based home kitchen waste, it forms a natural cycle with the harvested mealworms frozen for use in cooking. The Hive Explorer educates both adults and children and is available for schools to assist with teaching and learning initiatives around sustainability and food production systems.

While the company’s headquarters remains in Hong Kong in order to continue to pursue the Asian market, a separate branch opened in Vienna in 2019 to work on industrializing its insect farming, automated technology working with a variety of species. The aim is to breed insects in a modular, mobile breeding station which can be adapted to the size and requirements of each location and customer, already piloted and trialled with the supermarket Lidl, Austria, utilizing food waste.

Looking to the future, LIVIN farms aims to become a technology provider for insect farming and with locations in both Europe and Hong Kong, there is plenty of opportunity to do this.

Unger states: ‘Our aim is to establish ourselves as a sustainable company in the field of alternative protein by building turnkey solutions as ‘plug & play’ systems with partners to turn their raw materials into high-quality proteins for not only livestock feed and pet food but also for human consumption.’

Within 5 years, LIVIN farms will be established in the fish feed market, but also in poultry and pig feed as Unger believes legislation will change soon to allow this, supported by the completion of their industrial-scale facility. Diversification into protein for human foods has already occurred and that can only grow.

'The one single factor that keeps me motivated to deliver against our ambitious objectives is the growing band of people who believe in this industry,' reflects Unger.

Innovation Article: nextProtein

nextProtein
feeding the future

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Fig. 13.9. Syrine Chaalala, Managing Director, and Mohamed Gastli, CEO, husband and wife team, and co-founders of nextProtein (left). Black soldier fly (BSF) larvae are used by nextProtein to convert food waste into animal feed (right).

Syrine Chaalala explains: 'Having worked in the world's poorest countries with the UN's FAO [Food and Agriculture Organization of the United Nations] and observed first-hand what climate change is doing to the most vulnerable populations, my husband – a chemical engineer and entrepreneur – and I decided we wanted to take things into our own hands. Our aim was to create a responsible business model that would provide concrete and sustainable solutions to the world's major interconnected issues – food insecurity, a growing population and food waste.'

'It just so happened that at the same time,' Syrine continues, 'I was working in Madagascar on an anti-locust programme during which we were introduced to the world of insects and discovered their amazing properties, as well as understanding the potential of this untapped natural resource to impact global food systems.'

Madagascar is one of the poorest countries in the world, and although the couple had been exposed to many poor countries before, Madagascar hit them both much more forcefully. The level of poverty and child mortality they saw motivated and encouraged them to quit their jobs and risk doing something that they believed had never been done in the world before – industrialized insect rearing for animal feed.

Initially, there was nothing out there to aid them, explains Syrine. There were no experts or past experience they could draw on, and no scientific literature, as technically this had never been done. Additionally, they knew nothing about insects!

Syrine explains: ‘So we started from scratch using our personal savings until we met – after thousands of cold calls and e-mails – a prominent European business angel, who believed in us and agreed to help in formalizing our business plan based on our unique business model. When the time was right, we were also helped to identify additional business associates for our seed round enabling us to create our proof of concept.’

From initial brain-storming and research in 2014 into BSF and their potential for protein and other added value products, nextProtein’s pilot plant was in operation by 2018 with support from start-up hubs and other services. The next challenges to be overcome were scaling up and the production of quantities viable to service the growing aquaculture and pet food markets.

nextProtein was backed by a range of high-profile European investors for their seed round, who recognized its potential to revolutionize the industry, by demonstrating that insects are the only sustainable and environmentally friendly alternative to the traditional protein sources of fishmeal and soya bean. Investors include crowdfunding equity platforms, business angel communities as well as top-ranked international and French-based individuals and organizations. This led to the establishment of the company’s 2500 m^2 production site on the African continent in Tunisia. Here nextMeal and nextOil, ingredients for animal feed, are produced together with nextGrow, a natural fertilizer from BSF frass for use in agriculture.

In its most recent fundraising efforts in March 2020, nextProtein raised €10.2 million (US$11.2 million) in Series A funding to scale up its production, the largest ever raised for an early stage food technology company in the region. This funding round was led by a group of investors coordinated by Blue Oceans Partners, a fund whose mission is to invest in innovations that help conserve and sustainably use the oceans. It is enabling nextProtein to build a second cutting-edge facility, hire new talent and accelerate its R&D programme. The company plans to scale production to 100 k/t/year by 2025, or an estimated 10% of the total insect protein market globally.

Now with a 40+ person team of engineers, technicians, researchers and corporate members, nextProtein keeps up with and contributes to the latest research and technology in the field. Within a short period of time, nextProtein expects to have positioned itself as a leader in the field and to grow significantly. It will have commissioned several other plants on other continents with an increased annual production capacity to meet the ever-increasing demands of not only the pet food and aquaculture sectors, but also the poultry and pig sectors, as legislation and regulation is adapted to allow the inclusion of insect protein.

‘In 5 years’ time, we see insect protein as solidly anchored in all segments of animal nutrition as a mainstream product,’ concludes Syrine, ‘with new insect species farmed for more specific applications across the feed sector. Feed remains our strategic focus, so as yet we are unlikely to diversify into human food, although this sector is predicted to expand exponentially.’

Innovation Article: Ÿnsect reinventing the food chain

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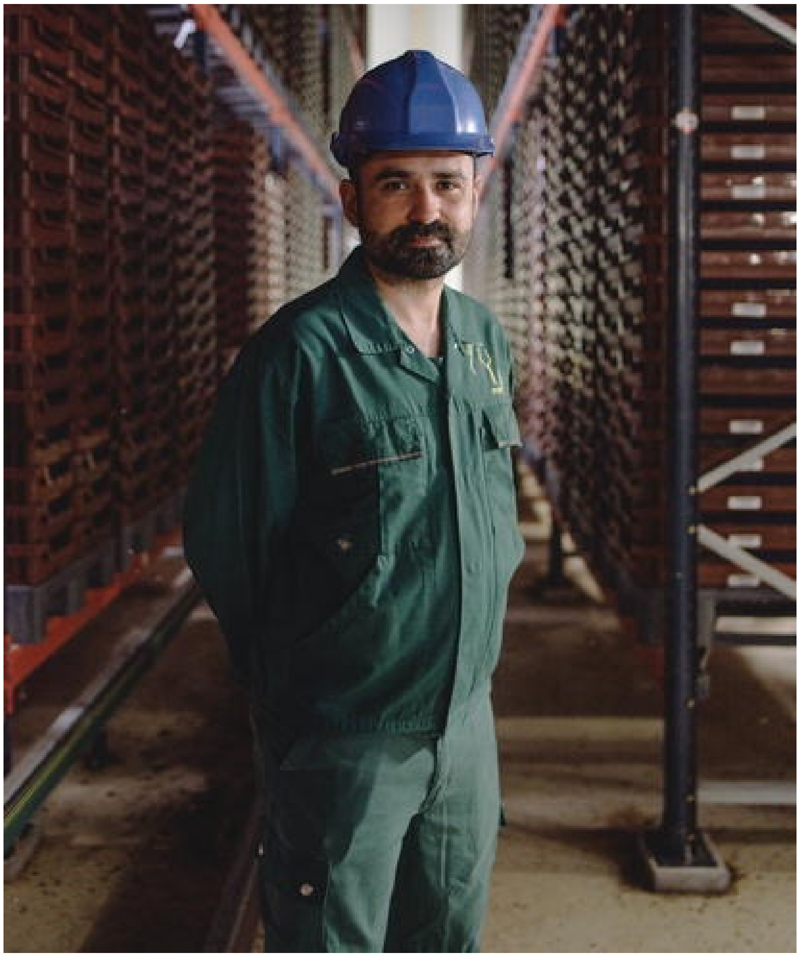

Fig. 13.10. Antoine Hubert, co-founder and CEO of Ÿnsect, in Ynsite, the company’s first vertical farm – Dole (France).

After his studies in France at Agrocampus Ouest and AgroParisTech in agricultural engineering, environment and ecology, Antoine Hubert worked as an engineer in a research centre in New Zealand. His focus on pollution and their solutions in forestry and other agricultural territories, in the form of waste recycling projects using earthworms, stood him in excellent stead for his move back to Paris and the non-governmental organization (NGO) space. Here he promoted the use of worms in schools and at home for recycling, composting and for growing fruits and vegetables. From his work developing tool kits for organic farming, waste processing and composting, Antoine created an extensive and valuable network of partners and contacts.

Hubert says: ‘By continuing to read and research, I and my colleagues came across the concept of insect farming – a practice that had been around for hundreds of years, but which was becoming more commercial in Asia, with applications for both animal feed and human food, with even the United Nations now promoting the concept.’

Antoine and close colleagues added the concept to their NGO work programmes but became increasingly frustrated at the gap between providing education on these concepts and their implementation. So instead of talking about it, Antoine Hubert, Jean-Gabriel Levon, Alexis Angot and Fabrice Berro seized on the idea and turned it into a for-profit company. In 2011, Ÿnsect was born, based on what many perceived at that time as the ‘crazy idea’ of putting the insect back in the place where it should always have been – at the very heart of the food chain.

‘Our core objective,’ states Hubert, ‘was to demonstrate that it is possible to create a new local industry to feed the world, whilst also conserving and protecting the planet’s resources and its biodiversity.’

As well as creating an innovative and potentially disruptive idea, entrepreneurs also require the context and time to be right for their idea to flourish. Ÿnsect emerged at a time when the issues creating one of the world’s most challenging topics reached its ‘nexus’ – the increased demand for protein and plants worldwide to feed its growing population, combined with dwindling land, soil, water and fish resources increasing greenhouse gas emissions.

‘With the UN’s FAO predicting that consumption of animal proteins will grow by 52% from the early 2000s to 2030 causing a huge spike in demand for protein and plants, it brought the risk to the world’s already fragile ecosystems into sharp focus,’ explains Hubert, adding that the current COVID-19 crisis has confirmed that food supply chains remain fragile.

Ÿnsect embarked on a period of intense research and development, initially as part of the DESIRABLE project which focused on designing the optimum insect biorefinery. Incubated by Agoranov, the science and tech incubator based in Paris, the Ÿnsect team became involved in many national and European funded projects, for example with INRAE (Institut national de la recherche agronomique), the public research institute dedicated to agricultural science.

‘Insect was a brand new ingredient, so we had to prove to our client prospects that it could bring significant benefits by replacing traditional animal proteins and chemical fertilizers with Ÿnsect products,’ says Hubert.

The evidence base has developed with scientific studies demonstrating that using

Ÿnsect's mealworm-based products as replacements benefit both yield and health, for example 40% and 25% mortality reduction in shrimp and sea bass, respectively, and a 25% increase in rapeseed yield with the use of its frass. Today, Ÿnsect has over US$100 million worth of contracts signed with customers across aquaculture and agricultural sectors.

The relevant regulatory framework for the use of insect ingredients did not exist 10 years ago. The growing Ÿnsect team worked with French and European institutions, together with many other researchers and businesses, to adapt and change that framework – work that wasn't easy and, above all, not always fast enough to meet market and business needs. Collaboration was key and the establishment in 2012 of the business 'trade' organization IPIFF has proved key, coupled with Ÿnsect's success in building its own reputation and securing funding.

In 2014 €1.8 million of funding was secured, providing new offices and laboratories within the Genopole® Biocluster, followed in 2015 by more than €11 million from private and public sources, enabling Ÿnsect to build its first Ynsite, it's first 'Fermilière' – a farmhouse for the conversion of insects into proteins – incorporating the company's breakthrough technologies. By 2016, the company delivered its first mealworm products to customers in the pet food sector, while also working on the submission of 20 registered patents. A step change in the sector overall and for Ÿnsect came in 2017 with EU authorization for insect protein in aquaculture, with discussions continuing (as at January 2021) for its inclusion in poultry and pig feed.

In 2020, Ÿnsect was selected as part of France's 'next40' programme for late-stage French start-ups with potential as a global technology leader, and with funding of US$372 million it began to build the largest vertical insect farm in the world (a carbon negative project). The company remains on track to launch its mealworm products for human consumption, with submission of a Novel Food dossier in late 2020, accelerated by the European Food Safety Authority's (EFSA) positive opinion on the use of mealworms in food on 13 January 2021. The massive US fitness and sports nutrition markets are next, with commercial contracts already signed.

'From 2011 with one idea and four co-founders, with complementary skills and entrepreneurial experience, to 150 'ynsectors' today, motivated to improve the world food chain,' concludes Hubert, 'we continue to discover new health and performance properties of insect protein for animals, plants, humans and the planet.'

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14 Legislation, Policy and Quality Assurance

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14.1 Introduction

Insects are a natural source of nutrients for some livestock groups. Thus, an opportunity for their use as a feed material should arise in view of the predictions for global population growth over the coming years and any increased demand for meat and competition for growing crops for both human and animal use.

At the same time, however, challenges lie ahead for producers and suppliers of insect-derived feed materials. Reference, for example, *FAO Forestry Paper 171*, 'Edible insects: future prospects for food and feed security': Regulatory frameworks governing food and feed chains have expanded tremendously in the last 20 years; however, regulations governing insects as food and feed sources are still largely absent. For developed countries, the absence of clear legislation and norms guiding the use of insects as food and feed is among the major limiting factors hindering the industrial development of farming insects to supply the food and feed sectors. In developing countries, the use of insects for human or animal food is, in practice, more tolerated than regulated.

(van Huis *et al*., 2013, p. 18)

14.2 Current Legislation

The first part of the chapter summarizes current feed legislation controlling the production and use of insect-derived feed materials. The information relating specifically to countries outside the UK and European Union (EU) is neither detailed nor complete due to sourcing difficulties. This information is provided in good faith and, in all cases, it is necessary to consult the legislation per se if more information is required.

The International Platform of Insects for Food and Feed (IPIFF) *Guide on Good Hygiene Practices: for European Union (EU) Producers of Insects as Food and Feed* (IPIFF, 2020) also provides details of the current legislation.

14.3 UK and EU Feed Legislation

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Background

A series of food safety incidents towards the end of the last century and beginning of the 21st century resulted in a comprehensive revision of UK/EU food and feed safety controls. The purpose was to better protect animal and human health, the environment, and reassure consumer confidence in food production. At a similar time, feed quality assurance schemes covering the production and supply of individual feed materials and compound feed were introduced. These operate in the UK and several EU countries. They support feed legislation, dovetail into farm assurance schemes and some individual retailer requirements as well as independent standards.

Two sets of regulations, Regulation 999/2001 on transmissible spongiform encephalopathies (TSEs) (European Commission, 2001) and Regulation 1069/2009 on animal by-products (ABPs) (European Commission, 2009b), together with Regulation 142/2011 (European Commission, 2011) laying down the detailed ABP implementation rules, are of note and present challenges to the production and use of insect protein. The TSE Regulation was adopted to protect human and animal health from the risk of bovine spongiform encephalopathy (BSE) and is underpinned by the ban on intra-species recycling and the prohibition of the use of certain ruminant materials in feed (i.e. the feed ban). This regulation currently only permits the use of insect protein in feed for aquaculture animals and pets. The intra-species ban includes onerous controls on the transport and storage of processed animal protein (PAP) and derived products, including insect protein, and their use on production lines in feed mills. These controls could restrict the use of insect protein in feed mills with single production lines when it is authorized for use in pig and/or poultry feeding stuffs. Guidance from the appropriate national authority/authorities will be necessary to ensure compliance with any future modifications of the feed ban. This restriction could also apply to some retailer and/or independent standards on feed material usage and compound feed production.

The ABP Regulation (European Commission, 2009b) was introduced following the foot-and-mouth crisis and the occurrence of dioxins in feeding stuffs. These crises showed the consequences of the improper use of certain ABPs, including ruminant and non-ruminant sources, for both public and animal health. The ABP Regulation laid down detailed provisions on the validation of processing facilities and control. Also, for insect protein, they control the specific substrates that can be used for insect farming.

Content of legislation

Producers, suppliers and users of feed materials derived from insects and compound feed containing them are subject, as relevant, to all the UK/EU feed legislation, which includes:

- controls on traceability (Regulation 178/2002 on general principles of food and feed law; European Commission, 2002a);
- appropriate registration/authorization, compliance with good hygiene practices,

application of Hazard Analysis and Critical Control Point (HACCP) principles and recall procedures (Regulation 183/2005 on feed hygiene; European Commission, 2005);

- necessary labelling information on composition and use of the feed and/or compound feed into which it has been incorporated (Regulation 767/2009 on the marketing and use of feed; European Commission, 2009a; and Commission Regulation 2017/1017 on the Catalogue of Feed Materials; European Commission, 2017);
- controls on contaminants, for example heavy metals, mycotoxins, dioxins, PCBs (polychlorinated biphenyls) and certain pesticides (Directive 2002/32 on undesirable substances in animal feed; European Commission, 2002b); and
- permitted feed additives (Regulation 1831/2003; European Commission, 2003).

Insects intended for food and/or feed have the legal status of 'farmed animal' (reference Article 3.6 of ABP Regulation 1069/2009; European Commission, 2009b) which is defined as: (a) Any animal that is kept, fattened or bred by humans and used for the production of food, wool, fur, feathers, hides and skins or any other product obtained from animals or for other farming purposes;

(b) Equidae.

(European Commission, 2009b, Article 3.6)

The general requirements for animal health also apply to insects. Insect producers must therefore comply with animal health and biosecurity measures on transmissible animal diseases, as contained in Regulation 2016/429, the 'Animal Health Law', (reference Article 10) (European Commission, 2016). Thus, insect species and products thereof shall not be pathogenic or have other adverse effects on plant, animal or human health. Insects are, however, exempted from the application of the EU animal welfare legislation, which only concerns vertebrate animals.

Under current UK/EU feed legislation, there are five insect-derived feed materials listed in the Catalogue of Feed Materials, Category 9 – 'Land animal products and products derived thereof'. With specific reference to insect protein, this falls within the definition of 'processed animal protein' (PAP) and is also referred to in official guidance as insect PAP or PAP from farmed insects.

The five listed entries are: (i) PAP; (ii) animal fat; (iii) hydrolysed animal protein; (iv) terrestrial invertebrates, live; and (v) terrestrial invertebrates, dead.

Details about PAP are as follows: 9.4.1 Processed animal protein – defined as:

- Product obtained by heating, drying and grinding whole or parts of land animals, including invertebrates other than species pathogenic to humans and animals in all their life stages from which the fat may have been partially extracted or physically removed. If extracted with solvents, may contain up to 0.1% hexane.
- Compulsory declarations on the feed label:
  - Crude protein;
  - Crude fat;
  - Crude ash;
  - Moisture if > 8%.

(European Commission, 2017)

As previously stated, UK/EU legislation currently only permits the use of insect protein in feed for aquaculture animals and pets. However, the following four insect-derived feed materials may be fed to any farm animals, including ruminants. 9.2.1. Animal fat – defined as:

- Product composed of fat from land animals, including invertebrates other than species pathogenic to humans and animals in all their life stages. If extracted with solvents, may contain up to 0.1% hexane.
- Compulsory declarations on the feed label of:
  - Crude fat;
  - Moisture if > 1%.

9.6.1 Hydrolysed animal proteins defined as:

- Polypeptides, peptides and amino acids, and mixtures thereof, obtained by hydrolysis of animal by-products, which can be concentrated by drying.
- Compulsory declarations on the feed label:
  - Crude protein;
  - Moisture if > 8%.

9.16.1 Terrestrial invertebrates, live defined as:

- Live terrestrial invertebrates, in all their life stages, other than species having adverse effects on plant, animals and human health.

9.16.2 Terrestrial invertebrates, dead defined as:

- Dead terrestrial invertebrates, other than species having adverse effects on plant, animals and human health, in all their life stages, with or without treatment but not processed as referred to in Regulation (EC) No 1069/2009.
- Compulsory declarations on the feed label:
  - Crude protein;
  - Crude fat;
  - Crude ash.

(European Commission, 2017)

UK feed legislation is currently in line with the EU controls. The UK Government has provided detailed guidance on the following:

- TSE Regulation 999/2001 (European Commission, 2001) and the feed ban controls: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_d
  feed-controls.pdf (accessed 10 November 2020);
- The ABP Regulation 1069/2009 (European Commission, 2009b) and ABP Regulation

142/2011 (European Commission, 2011) which lays down detailed implementation rules for Regulation 1069/2009 (European Commission, 2009b). Guidance relating to the use of ABPs in farm animal feed can be found at: https://www.gov.uk/government/collections/guidance-for-the-animal-by-product-industry#feeding-animals-abps (accessed 10 November 2020); and
- Feed hygiene and safety at: https://www.food.gov.uk/business-guidance/farming-animal-feed (accessed 10 November 2020).

To operate, UK/EU producers of insect protein need approval under the ABP Regulations with the appropriate national authority. They need to meet standards that apply across the ABP industry in areas including HACCP, record keeping and validation of processing facilities and control.

The ABP Regulations also cover the production, transport and storage of pet food. Under these regulations, sea or land invertebrates (spineless animals, e.g. insects) can be used in pet food production as long as they do not carry diseases that can be passed on to humans or animals. There are controls in place to prevent cross-contamination of feed for farmed livestock with pet food containing such ingredients. The manufacture of pet food is an activity that must be approved under the ABP Regulations.

For further details on the limitation on the production and use of insect-derived products see section 14.6 ‘Legal Limitations on Production and Use of Insect-derived Feed Materials in the UK/EU’ later in this chapter.

Proposed amendments to TSE Regulation 999/2001

In October 2020, a draft regulation was released amending Annex IV to Regulation 999/2001 (European Commission, 2001) providing for the:

- authorization of insect PAP in pig and poultry feed; and
- re-authorization of pig PAP in poultry feed, the re-authorization of poultry PAP in pig feed and the lifting on the ban on ruminant gelatin and collagen in non-ruminant feed.

A key feature of Regulation 999/2001 is the prohibition on intra-species recycling, thus the proposal requires a zero tolerance approach and strict dedication of feed-mill production facilities so that where, for example, pig PAP is used in poultry feed it must be segregated from pig feed. The proposal would, however, permit the use of insect protein in:

- a pig and poultry feed mill that used neither pig PAP nor poultry PAP;
- a pig-only mill that used poultry PAP; and
- a poultry-only mill that used pig PAP.

The proposal is scheduled for discussion at EU Commission TSE Working Group level and negotiations are likely to continue into 2021. As the UK left the EU single market and EU Customs Union at the end of 2020, any future agreement on the proposal at EU level will not be applied in the UK. However, it is understood that the UK Government will be reviewing the proposal in detail as it is likely to result in structural changes to the National Feed Audit, with consequent amendments to the ‘The Transmissible Spongiform Encephalopathies (England) Regulations 2010’ and similar amendments to the parallel regulations in the devolved administrations.

14.4 Feed Legislation for Countries Outside the UK/EU

Australia

The Australian Pesticides and Veterinary Medicines Authority (APVMA) has developed a decision tree on feed materials available at the following link: https://apvma.gov.au/sites/default/files/docs/stockfood_decision_flowchart.pdf (accessed 10 November 2020).

Canada

All feed and feed ingredients are regulated by the Canadian Food Inspection Agency (CFIA). The CFIA developed an entry under Section 5 (Protein Feeds), Part II of Schedule IV of the Feeds Regulations, 1983 (SOR/83-593; Gouvernement du Canada, no date) for dried whole insect larvae as an ingredient in feeds for broiler chickens. The entry for ‘Dried whole insect larvae’ included in the Feeds Regulations, 2018 is as follows:

- 5.19 Dried Whole Insect Larvae – is the larvae of insects grown on and fed a substrate that is acceptable for the production of safe and nutritious livestock feeds. Whole larvae are harvested and cleaned to be free of growth substrate. They are then treated, dried, and may be ground.
    - It is approved as a source of protein and energy for use in feeds for broiler chickens.
    - If it bears the name descriptive of its kind (e.g. black soldier fly) or form (i.e. ground), it shall correspond thereto, and it may be indicated on the label.
    - This product shall be processed in accordance with good manufacturing practices and be free of harmful microorganisms.
    - It shall be labeled with guarantees for minimum percent crude protein, minimum percent crude fat, maximum percent ash, and maximum percent moisture.

(unpublished material supplied by Dr Elizabeth Lewis, Secretary General of BAFSAM (British Association of Feed Supplement and Additive Manufacturers), 2020)

Each source of dried whole insect larvae must be registered with the CFIA prior to placing on the market.

At the time of writing, it is understood that the Schedule online is not up to date (available (CFIA, no date).

China

The Chinese Ministry of Agriculture (MOA) brought Decree No.1773 on the Feed Ingredient Catalogue into operation on 1 January 2013 (MOA, 2012a). The Feed Ingredient Catalogue lists the individual feed ingredients that need to have a production licence or import registration certificate. It is based on 'the Administrative Measures on Feed and Feed Additives'.

Production, trade, and the use of feed ingredients listed in the Feed Ingredient Catalogue shall meet the mandatory requirements as specified in the documents entitled: 'Feed Hygienic Standard' and 'Feed Labelling'.

The insect-derived feed materials are listed and referred to as follows. 9.2 Processed insect products

9.2.7 Insect (meal) – defined as:

- Dried insects, that are crushed. Only insects that do not affect public health or animal health can be processed in this way. The product name shall indicate the specific animal species, such as: yellow mealworm insect (meal).
- Declarations:
    - Crude protein;
    - Crude fat;
    - Acid value.

9.2.8 De-fatted insect powder – defined as:

- Insects (meal) is de-oiled through supercritical fluid extraction and other methods. Only insects that do not affect public health or animal health can be processed in this way. The product name shall indicate the specific animal species, such as: de-fatted yellow mealworm insect meal.
- Declarations:
    - Crude protein;
    - Crude fat.

(MOA, 2012b)

Substances that are not listed in the Feed Ingredient Catalogue shall undergo scientific evaluation and be approved by the Chinese MOA. After evaluation, the MOA may add new substances to the catalogue. If added, the substances can be used as a feed ingredient. If a new feed material is produced outside China, it must be registered as a new material and complete import registration requirements.

USA

The US Food and Drug Administration (FDA) governs food safety. Under the Federal Food, Drug, and Cosmetic Act (FFDCA) any substance that is added to or is expected to become an ingredient or additive of animal food and feed (directly or indirectly) must be in accordance with section § 348 Food Additives if it has not been generally recognized as safe (GRAS) for that use.

All feed ingredients must be listed in the Association of American Feed Control Officials (AAFCO) Official Publication (OP) (as ingredient definitions, food additives or GRAS substances) for the intended use. To date, only black soldier fly larvae (dried whole larvae, defatted meal) are permitted in animal feed in accordance with this ingredient definition in the AAFCO OP and referred to as follows: 60.117 Dried Black Soldier Fly Larvae – is the dried larvae of the Black Soldier Fly, *Hermetia illucens*, with or without mechanical extraction of part of the oil, that has been raised on a feedstock composed exclusively of feed grade materials. The ingredient must be labelled with guarantees for minimum crude protein and minimum crude fat on an as-fed basis. If the oil is mechanically extracted, maximum crude fat must also be guaranteed on the ingredient label. The ingredient is dried by artificial means to no more than 10% moisture. It is for use in salmonid and poultry feed as a source of protein and fat consistent with good feeding practices.

- It is understood that extending the above to pigs, and dogs is under review.

(AAFCO, 2020)

14.5 Quality Assurance

UK

The Agricultural Industries Confederation (AIC) Ltd has developed a range of trade assurance schemes covering areas of the agri-supply industry in which the UK agri-supply industry is engaged. Membership is open to members and non-members of the association. The three food/feed assurance schemes, which facilitate compliance with UK feed safety legislation as well as industry good practice, are:

- **UFAS** (Universal Feed Assurance Scheme) which deals with the production and delivery of compound feeds and the supply of feeds to the farm.
- **FEMAS** (Feed Materials Assurance Scheme) covers the sourcing and production of feed ingredients, either by certifying complete supply chains or by certifying a company to act as a ‘gatekeeper’ to the assured supply chain standard. The scheme includes a series of sector notes that are to be read in conjunction with the FEMAS Standard and aim to provide additional information on implementing the FEMAS scheme requirements in

specific industries. Currently, there is no sector note for insect-derived feed materials. However, producers of these feed materials could be certificated to FEMAS and should request AIC to develop a sector note for insect-derived feed materials if so required.

- **TASCC** (Trade Assurance Scheme for Combinable Crops) deals with the merchanting, haulage and storage of combinable crops (for food and feed use) and animal feeds.

Details of the schemes are available at: https://www.aictradeassurance.org.uk/about-trade-assurance/ (accessed 10 November 2020). All the schemes are operated by independent certification bodies under current accreditation from UKAS (United Kingdom Assurance Service). The schemes are managed in consultation with a variety of stakeholders including scheme participants and government along with customer and supplier groups.

Overseas assurance schemes

There is mutual recognition between the AIC feed assurance schemes and several European organizations representing the full range of feed materials supplied to farmed livestock. Details can be found on the AIC Services website: https://www.aictradeassurance.org.uk/overseas-schemes/ (accessed 10 November 2020).

14.6 Legal Limitations on Production and Use of Insect-derived Feed Materials in the UK/EU

ABP Regulation 142/2011 (European Commission, 2011) states that PAP derived from farmed insects, intended for the production of feed for farmed animals other than fur animals, *may only* be obtained from the following insect species: (i) black soldier fly (*Hermetia illucens*) and common housefly (*Musca domestica*); (ii) yellow mealworm (*Tenebrio molitor*) and lesser mealworm (*Alphitobius diaperinus*); and (iii) house cricket (*Acheta domesticus*), banded cricket (*Gryllodes sigillatus*) and field cricket (*Gryllus assimilis*).

TSE Regulation 999/2001 (European Commission, 2001) states that insect-PAPs may only be fed to pets and to ‘aquaculture animal’ – defined as: (i) fish belonging to the superclass Agnatha and to the classes Chondrichthyes and Osteichthyes; (ii) molluscs belonging to the Phylum Mollusca; and (iii) crustaceans belonging to the Subphylum Crustacea.

PAP derived from non-ruminant animals (including insect PAP) can only be used in feed for aquaculture animals, providing that systems are in place to ensure adequate separation from ABPs and PAP of ruminant origin, throughout the entire handling chain, from slaughter, through transport, storage and processing, at premises registered or authorized under the TSE Regulation for this purpose.

A method of analysis using double sedimentation and subsequent detection by light microscopy has been developed by EURL Animal Proteins to check the presence of insect PAPs in feed for food producing animal species other than fish (EURL Animal Proteins, 2019).

As regards insect-derived feed materials other than PAPs, they may be fed to any animal species and be produced from any insect species as long as it is not pathogenic or have other adverse effects on plant, animal or human health (Animal Health Law; European Commission, 2016), and is not defined as an invasive species in accordance with Regulation 1143/2014 (European Commission, 2014) on the prevention and management of the introduction and spread of invasive alien species.

The feeding of insects is subject to the same rules as the feeding of any other farmed animal meant for feed and/or food use. In addition to materials of vegetal origin, the following materials of animal origin are permitted under the TSE-related feed ban for farmed insects when sourced and processed in accordance with the ABP Regulations:

- milk, milk-based products and colostrum;
- eggs and egg products;
- collagen and gelatine derived from non-ruminants;
- hydrolysed proteins derived from parts of non-ruminants or from ruminant hides and skins;
- dicalcium phosphate and tricalcium phosphate of animal origin;
- fishmeal;
- blood products from non-ruminants;
- rendered fat; and
- honey.

Under the current ABP legislation, former foodstuffs containing meat and fish are not allowed as substrates. The ABP legislation also applies additional controls preventing unprocessed ABPs being used for animal feed purposes, with certain exceptions, including milk/milk products under national controls and foodstuffs no longer intended for human consumption, such as surplus bakery and confectionary products, when not containing or in contact with meat or fish products. For further information see:

- https://www.gov.uk/guidance/using-leftover-milk-and-milk-products-as-farm-animal-feed (accessed 1 November 2020); and
- https://www.gov.uk/guidance/supplying-and-using-animal-by-products-as-farm-animal-feed (accessed 1 November 2020).

Regulation 767/2009 (European Commission, 2009a) on the marketing and use of feed lists the following *prohibited materials*:

1. Faeces, urine and separated digestive tract content resulting from the emptying or removal of digestive tract, irrespective of any form of treatment or admixture.
2. Hide treated with tanning substances, including its waste.
3. Seeds and other plant-propagating materials which, after harvest, have undergone specific treatment with plant-protection products for their intended use (propagation), and any by-products derived therefrom.
4. Wood, including sawdust or other materials derived from wood, which has been treated

with wood preservatives as defined in Annex V to Directive 98/8/EC of the European Parliament and of the Council of 16 February 1998 (European Commission, 1998) concerning the placing of biocidal products on the market.

5. All waste obtained from the various phases of the treatment of the urban, domestic and industrial wastewater.

6. Solid urban waste such as household waste.

7. Packaging from the use of products from the agri-food industry, and parts thereof.

8. Protein products obtained from yeasts of the *Candida* variety cultivated on *n*-alkanes.

14.7 Likelihood of Further Use of Insects in Animal Feed Being Allowed in the EU

As previously stated, the current EU food and feed safety controls have been totally revised in order to better protect animal and human health and address the loss of consumer confidence in food production.

The European Green Deal

At the end of 2019, the European Commission published ‘The European Green Deal’ (European Commission, 2019). This was followed, in May 2020, by the release of the ‘Farm to Fork Strategy on Sustainable Food Systems – Draft Action Plan’ (European Commission, 2020) which is a key component of the European Green Deal. Included in a section to ‘Stimulate the production of more sustainable feed materials and food’ is the statement on adapting regulations on feed marketing, ABPs and TSEs to facilitate the use of more sustainable feed materials including protein feed, grown on new substrates for insects.

The following are relevant extracts from the ‘Farm to Fork Strategy’: Section 2 – Building the Food Chain that works for consumers, producers, climate and the environment

> 2.1. Ensuring sustainable food production
>
> Agriculture is responsible for 10.3% of the EU’s GHG [greenhouse gas] emissions and nearly 70% of those come from the animal sector. They consist of non-CO_2 GHG (methane and nitrous oxide). In addition, 68% of the total agricultural land is used for animal production. To help reduce the environmental and climate impact of animal production, avoid carbon leakage through imports and to support the ongoing transition towards more sustainable livestock farming, the Commission will facilitate the placing on the market of sustainable and innovative feed additives. It will examine EU rules to reduce the dependency on critical feed materials (e.g. soya grown on deforested land) by fostering EU-grown plant proteins as well as alternative feed materials such as insects, marine feed stocks (e.g. algae) and by-products from the bio-economy (e.g. fish waste). Furthermore, the Commission is undertaking a review of the EU promotion programme for agricultural products, with a view to enhancing its contribution to sustainable production and consumption, and in line with the evolving diets. In relation to meat, that review should focus on how the EU can use its promotion programme to support the most sustainable, carbon-efficient methods of livestock production. It will also strictly assess any proposal for coupled support in Strategic Plans from the perspective of the need for overall sustainability.
>
> (European Commission, 2020, p.7)

> Section 3 – Enabling the transition
>
> 3.1. Research, innovation, technology and investments
>
> Research and innovation (R&I) are key drivers in accelerating the transition to sustainable, healthy and inclusive food systems from primary production to consumption. R&I can help develop and test solutions, overcome barriers and uncover new market opportunities. Under Horizon 2020, the Commission is preparing an additional call for proposals for Green Deal priorities in 2020 for a total of around EUR 1 billion. Under Horizon Europe, it proposes to spend EUR 10 billion on R&I on food, bioeconomy, natural resources, agriculture, fisheries, aquaculture and the environment as well as the use of digital technologies and nature-based solutions for agri-food. A key area of research will relate to microbiome, food from the oceans, urban food systems, as well as increasing the availability and source of alternative proteins such as plant, microbial, marine and insect-based proteins and meat substitutes.
>
> (European Commission, 2020, p.16)

14.8 Further Possible Amendments to Regulation 999/2001 on TSEs

Over the last few years, the authorization of use of insect protein in pig and poultry feed was registered on the EU Commission working programme and discussed at several meetings of the EU TSE Working Group. The Green Deal only takes over what was already in the pipeline. At the time of writing, the proposals are still in draft form, but it is understood that the objective is adoption at EU level in 2021. It is expected that the legislator will require that only compound feed manufacturing plants not producing feed for species other than fish, pig, poultry, pets and fur animals will be allowed to use insect PAP.

The extent to which insect PAP will be effectively used in pig and poultry feed will depend on its competitiveness in relation to traditional protein sources such as soya bean meal. It will also depend on consumer acceptance, retailer feed specifications as well as ethical and religious consideration. Due to the present restrictions on the use of insect PAP, the amount of insect fats available on the market is very limited but its use may increase as soon as the demand for insect PAP develops. Similarly, the use of the other insect-derived feed materials may increase as soon as the demand for insect PAPs develops. However, as with insect protein, the use of the four other insect-derived feed materials (animal fat; hydrolysed animal proteins; terrestrial invertebrates, live; and terrestrial invertebrates, dead) very much depends on their competitiveness and acceptance in the marketplace.

UK

It should be noted that the above two possible initiatives (the European Green Deal and amendments to TSE Regulation 999/2001) are for modification of EU legislation. As the UK is no longer a member state of the EU, the UK will no longer automatically align with EU legislation. So, in future, it will be for UK stakeholders to negotiate with the UK authorities on future modification to any feed legislation.

14.9 Assurance Standards Requiring Review to Enable the Use of Insect Protein

There are currently no assurance standards which cover insect production or the feeding of insects to livestock within the EU. The *Guide on Good Hygiene Practices: for European Union (EU) producers of insects as food and feed* produced by IPIFF gives best practice for the production of insect products for both food and feed (IPIFF, 2020). This highlights the need for assurance standards to include insect products as suitable feed materials for assured livestock production.

The Halal Standard

The Halal Authority Board's Worldwide Standard (Halal Authority Board, no date) is a comprehensive set of guidelines for the production of halal meat, food and drink. The guidelines cover all aspects of production to ensure the halal integrity of products, including food health and safety regulations, to prevent contamination from pork and other unacceptable derivatives. The 'Primary Production of Livestock', which includes farmed fish, is one of its five modules. Certain products are considered as 'haram' or strictly forbidden under the Halal Standard. Thus, any feed company that seeks certification against the Halal Standard will need to check its details.

14.10 Conclusions

This chapter highlights the challenges and complexities associated with enabling the incorporation of insect products into the animal feed supply chain. The inherent hurdles are not surprising when we consider that the potential for large-scale commercial insect rearing was not recognized during the inception of either the legislation framework or the development of the quality assurance schemes. However, it is important to note that any changes must be fully understood and evidence based in order to ensure the safe use of insect products in the food chain.

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15 Global Consumer Perception of Insects as Feed

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15.1 Introduction

Global challenges such as food security and climate change require high-output, sustainable food and feed production. In accordance with the United Nations, Sustainable Development Goal 12 'responsible consumption and production' is required to effect transformation towards a low-carbon, green economy (UN, 2015). Since feed, especially fishmeal, crop-based feed materials and the energy consumption for feed processing, are the major contributors to 'land occupation, primary production use, acidification, climate change, energy use and water dependence' (Mungkung *et al*., 2013), sustainable, high-performance feed alternatives are needed for which insects have been suggested (Veldkamp *et al*., 2012; van Huis *et al*., 2013; Makkar *et al*., 2014). Thus investment in insect rearing, farming and production of insect protein continues to skyrocket globally for both human consumption and animal feed (Payne *et al*., 2016; van Huis, 2020). An adoption of insects as feed on an industrial level is first and foremost hindered by regulatory aspects as discussed earlier in this book, and by the challenges of upscaling production, at a competitive price and acceptance. Acceptance by all stakeholders along the value chain, from feed production to livestock production and aquaculture to meat and fish consumption, is vital for a successful marketing and utilization of insects as feed.

The acceptance of insects as feed has three facets:

- the acceptance of the insect-containing feed by livestock and fish;
- the acceptance by farmers and feed producers; and
- the acceptance of the resulting meat, fish and other animal products by consumers.

The acceptance and feasibility to feed livestock and fish with a number of insect species has been shown (Barroso *et al*., 2014; Ssepuuya *et al*., 2017; Gasco *et al*., 2019a) and is not discussed here but described in detail in Part 1 of this book. This chapter provides a global overview of farmers' and stakeholders' as well as consumers' perception of insect-based feeds from the literature and discusses gaps, lessons learnt and future needs in order to improve the acceptance of insects as feed, as well as the acceptance of meat and fish fed with insect-containing feed.

15.2 Preference of Farmers and Stakeholders in the Feed Industry

The number of scientific studies on the acceptance of insects as feed by farmers and stakeholders is low. This is likely to be due to the lack of regulation or approval of insects as feed and a long-standing tradition, practice and acceptance of the use of insects as feed. There is a wide variation across the globe due to the history of entomophagy and the use of insects as feed or lack thereof. Insects are a traditional part of human and animal diets in some countries of the world but are not in others. Furthermore, in some countries the use of insects as feed is not permitted or only approved on a species-specific level for specific farmed animals (e.g. aquaculture). Beyond that, large-scale industrial production and use of insects as feed is not prevalent on a global level. It is doubtful that currently an increase in demand on an industrial level could be met competitively and at short notice.

The acceptance of insect feed by farmers and stakeholders from the feed industry is influenced by traditions (or lack thereof) as well as by regulation and approval. Moreover, it depends on price in comparison to conventional feed materials, reliable supply at a standardized quality, growth performance and taste acceptance by the animals as well as acceptance by consumers. Consumer perception and acceptance of the use of insect feed is considered as the cornerstone required for a positive impact on market and profit levels.

Africa

In West Africa, insects are used as feed on occasion, for instance in the case of plagues of locusts or grasshoppers. In addition, termites are traditionally collected in the wild as chicken feed and fly larvae are used in fish and livestock feed. Usually the flies are reared on organic waste material that is freely available (Kenis *et al*., 2014). It can be concluded that there is a traditional acceptance of the use of insects as feed by farmers in West Africa.

In a cross-sectional survey with fish farmers, feed traders and processors in Uganda, a willingness to use insects as feed of above 90% was obtained for all three groups. However, experience with insects as feed was limited, especially for feed traders and processors and encompassed only feed insects collected in the wild. A positive perception of insects as feed was linked with familiarity and positively correlated with the notion that insects were a good nutritional feed source in aquaculture (Ssepuuya *et al*., 2019). In a similar study with poultry farmers, feed traders and processors in Uganda, a willingness to use insects as poultry feed of above 70% was obtained. Nevertheless, the poultry farmers expressed doubts in sufficient supply of insect feed, as well as in consumers’ acceptance of meat derived from chicken fed insect-based feed (Sebatta *et al*., 2019).

A survey of 957 pig, poultry and fish farmers in Kenya also indicated a potential market acceptance of insects as feed ingredients for livestock. Many factors were found to influence willingness to pay (WTP) for insect-based feed. These include for example socio-demographic aspects, distance to feed traders and use of commercial feed. It was proposed that educating feed millers and feed traders as to the benefits of insects as feed would enhance the WTP of Kenyan farmers. However, it was also cautioned that currently Kenya is not equipped to sustainably produce insects to meet the potential market demand (Chia *et al*., 2020).

America

In the USA and Canada, *Hermetia illucens* (black soldier fly; BSF) is approved in salmonid and poultry feed. Since its approval between 2016 and 2018, insect feed companies have been established in North America and both feed and animal production industries are receptive to the use of insects in feed. However, industrial-scale production volume has not yet been achieved to secure insect meal as an established feed ingredient (*FeedStrategy*, 2018; Einstein-Curtis, 2019).

In Brazil, legislation is to date unclear, since insects have not been anticipated as animal feed (Allegretti *et al*., 2018). At the moment, insect feed production is small scale only and not cost-effective. If increased demand from poultry, pig and fish production were to occur, that demand could not currently be met (Azevedo, 2019). There is a need for research and investment for cost-effective, sustainable insect production on a large scale. It has been proposed here that the use of poultry manure as a rearing substrate could significantly reduce waste volume and costs for waste treatment as well as benefit small farmers (Allegretti *et al*., 2018).

Asia

Insects are used as feed throughout the Asia Pacific region (Yen, 2015). For example, in China, *Musca domestica* (house fly (HF) larvae; HFL) are used as feed for poultry (Zhang *et al*., 2008). It has been suggested that appropriate insect species have a huge future potential for development on an industrial scale (Yen, 2015). However, for insect farmers, consumer acceptance of meat and fish derived from insect-fed production is crucial due to its impact on the potential market (Moon and Lee, 2015). Han *et al*. (2017) identified costs, competitiveness and upscaling of insect production as barriers to the South Korean insect sector.

Australia

In Australia, insect protein is currently fed to fish and poultry. Studies to pave the way for insects as feed for pigs are underway. Insects like the BSF are already reared on a large scale on organic waste (by companies such as Goterra, Waste Not Food Recycling and Moby) and marketed to the feed industry (Hein, 2020). Thus, it is assumed that there is a market for insects as feed for fish and poultry and stakeholder acceptance already exists.

Europe

Since 2017, in the European Union (EU) the use of seven insect species, BSF, HF, yellow mealworm (YM; *Tenebrio molitor*), lesser mealworm (LM; *Alphitobius diaperinus*), house cricket (HC; *Acheta domesticus*), banded cricket (BC; *Gryllodes sigillatus*) and field cricket (*Gryllus assimilis*; FC) are allowed in feed for aquaculture (Commission regulation (EU) 2017/893; European Commission, 2017). Insect feed for farmed animals is to date prohibited in the EU, but an authorization of insect protein as poultry and pig feed is currently being considered. The EU-organization International Platform of Insects for Food and Feed (IPIFF) aims to promote the use of insects as food and feed and represents the interests of stakeholders of the insect sector towards EU policy makers and other stakeholders. Browsing publications on their website, it appears that there is no focus on consumer acceptance of insects as feed to date. In fact, other research priorities concerning sustainable rearing and nutritional aspects have been prioritized (IPIFF, 2019).

In 2015, Verbeke *et al.* (2015) investigated the acceptance of insects as feed by farmers and stakeholders in Belgium. They observed that the participants of an electronic survey at a research fair generally had a positive attitude towards the use of insects as feed. Livestock farmers and in particular livestock farmers of ruminants were more critical towards insects as feed than stakeholders from other agricultural sectors. The survey concluded that the focus should be on insects as feed for fish, poultry and pigs since insects were not perceived as appropriate feed for beef and dairy cows. Marketing was perceived an important key to successful adoption of this feedstuff, whereas technological and quality management issues were seen as less problematic.

Popoff *et al.* (2017) revealed in semi-structured interviews with a salmon farmer, feed producers and a fish retailer, that all parties were open to the use of insects as feed. The US insect producer viewed upscaling and costs of insect production, product safety and competitiveness as challenges. This was confirmed in the paper by a Norwegian aquafeed producer who considered feed safety, legal approval, upscaling and price-competitiveness as challenges and potential fishmeal replacement as a benefit. They demanded an added-value benefit and feared potential rejection from supermarkets. The Norwegian fish farmer expected consumers to be indifferent towards the fish feed as long as the salmon production was environmentally friendly, and the fish was safe, healthy and tasty. Investments from the feed industry were seen as a requirement. The UK retailer attached importance to consumer trust and loyalty induced by information and communication. They demanded consumer research to prove a positive consumer attitude towards the use of insects in aquafeed. In summary, conditions for the adoption of insects as feed for salmon included a competitive price, feed safety, reliable supply and quality, additional benefits for producers, as well as consumer acceptance (Popoff *et al.*, 2017).

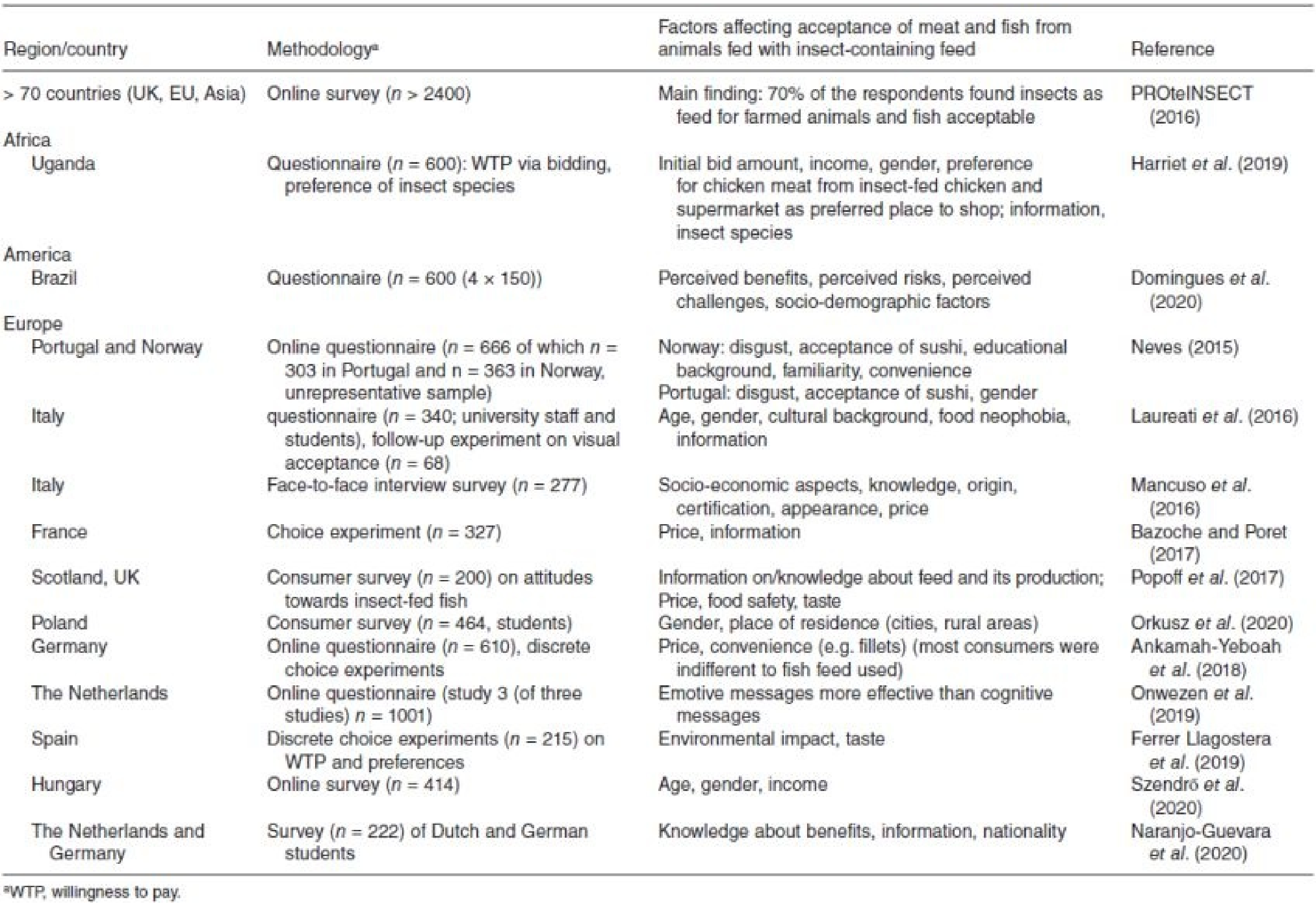
15.3 Preference of Consumers

In contrast to insects as food, the number of consumer studies regarding consumers' preference of insects as feed is low and appear limited in scope. This might be due to the fact that while feed production and use is generally regulated, the feed used to rear livestock and fish is usually not disclosed on the label of the animal product so that the consumer cannot identify the feed used when purchasing at the retailer. However, in comparison to consumer studies on the use of fishmeal or blood meal as feed, the studies on use of insect meal are numerous. A web of science search on 31 December 2020 of 'consumer acceptance fishmeal feed' and 'consumer acceptance blood meal feed' resulted in no consumer studies on those feed ingredients, while 'consumer acceptance soy meal feed' scored one hit. This demonstrates that there are not many consumer studies at all on the acceptance of feed ingredients. Consumers have traditionally not been concerned or informed about feed ingredients in general. However, awareness is now increasing mainly due to negative impacts of soya and fishmeal owing to deforestation and overfishing on climate and biodiversity, respectively.

Nevertheless, it is important to know consumers' preferences in order to develop successful marketing strategies and campaigns and mitigate negative reactions. Sustainable alternatives for fishmeal in aquaculture are needed and insects are currently predominantly used in aquaculture worldwide, with studies on the acceptance of insect-fed fish dominating the literature.

In this chapter, an overview of consumer studies is given which is summarized in Table 15.1. It shows that it cannot automatically be assumed that in countries like Brazil, where entomophagy has tradition, acceptance of insects as feed or food should be high. Probably due to urbanization and westernization, knowledge on collection, separation and consumption of insects is lost along with a positive attitude towards insect consumption. Moreover, acceptance of insects as food and insects as feed do not necessarily correlate.

Table 15.1. Overview of studies on consumer preference of insect feed.



Region/country	Methodology[a]	Factors affecting acceptance of meat and fish from animals fed with insect-containing feed	Reference
> 70 countries (UK, EU, Asia)	Online survey ($n > 2400$)	Main finding: 70% of the respondents found insects as feed for farmed animals and fish acceptable	PROteINSECT (2016)
Africa			
Uganda	Questionnaire ($n = 600$): WTP via bidding, preference of insect species	Initial bid amount, income, gender, preference for chicken meat from insect-fed chicken and supermarket as preferred place to shop; information, insect species	Harriet *et al.* (2019)
America			
Brazil	Questionnaire ($n = 600$ (4 × 150))	Perceived benefits, perceived risks, perceived challenges, socio-demographic factors	Domingues *et al.* (2020)
Europe			
Portugal and Norway	Online questionnaire ($n = 666$ of which $n = 303$ in Portugal and n = 363 in Norway, unrepresentative sample)	Norway: disgust, acceptance of sushi, educational background, familiarity, convenience Portugal: disgust, acceptance of sushi, gender	Neves (2015)
Italy	questionnaire ($n = 340$; university staff and students), follow-up experiment on visual acceptance ($n = 68$)	Age, gender, cultural background, food neophobia, information	Laureati *et al.* (2016)
Italy	Face-to-face interview survey ($n = 277$)	Socio-economic aspects, knowledge, origin, certification, appearance, price	Mancuso *et al.* (2016)
France	Choice experiment ($n = 327$)	Price, information	Bazoche and Poret (2017)
Scotland, UK	Consumer survey ($n = 200$) on attitudes towards insect-fed fish	Information on/knowledge about feed and its production; Price, food safety, taste	Popoff *et al.* (2017)
Poland	Consumer survey ($n = 464$, students)	Gender, place of residence (cities, rural areas)	Orkusz *et al.* (2020)
Germany	Online questionnaire ($n = 610$), discrete choice experiments	Price, convenience (e.g. fillets) (most consumers were indifferent to fish feed used)	Ankamah-Yeboah *et al.* (2018)
The Netherlands	Online questionnaire (study 3 (of three studies) $n = 1001$)	Emotive messages more effective than cognitive messages	Onwezen *et al.* (2019)
Spain	Discrete choice experiments ($n = 215$) on WTP and preferences	Environmental impact, taste	Ferrer Llagostera *et al.* (2019)
Hungary	Online survey ($n = 414$)	Age, gender, income	Szendrő *et al.* (2020)
The Netherlands and Germany	Survey ($n = 222$) of Dutch and German students	Knowledge about benefits, information, nationality	Naranjo-Guevara *et al.* (2020)

[a] WTP, willingness to pay.

Consumer studies on consumer preferences regarding insects as feed for livestock and aquaculture suggest that acceptance will not be a barrier towards the development of the insect protein industry for feed (Sogari *et al.*, 2019). While factors widely differ in approach and scope and are hardly comparable, it can be concluded that there are a vast number of indicators impacting consumer preference. These factors include – but are not limited to – socio-demographic factors, price, knowledge and information on feed and insect production, food neophobia and disgust and last but not least taste of the meat or fish (see Table 15.1).

A cross-country-continental consumer survey was conducted by the EU-funded research project PROteINSECT and involved more than 2400 respondents from more than 70 countries (including the UK, EU and Asia). It was shown that more than 70% of the respondents found insects as feed for farmed animals and fish acceptable and 73% stated that they would eat fish, poultry and pork fed with insects. While 88% said that they would like to have more information on the topic, 64% of the respondents perceived insect-based feed for farmed animals and fish as no or low risk for human health (PROteINSECT, 2016). It can be concluded that the overall acceptance of insects as feed appears to be high according to this survey.

Africa

Even though insects are a natural feed source for animals and traditionally used as feed in West Africa (see section 15.2, this chapter), consumer acceptance of insects as feed needs to be improved and promoted, especially in urban areas (Kenis *et al*., 2014).

Harriet *et al*. (2019) investigated consumers' WTP and their preferences for chicken meat from chicken fed five different insect species (termites, grasshoppers, crickets, BSF, HFL) in Kenya and found that chicken fed with BSF or HFL were least preferred. While 61% of all participants showed a WTP slightly more than the current market price some 19% were only willing to pay a discount price for meat from chicken that were fed insects. The authors attributed this to the information on benefits of insects as feed given to the participants beforehand (better texture, better taste, high nutritional quality, low fat content of the chicken meat). Factors influencing WTP obtained in this study included initial bid amount, income, gender, preference for chicken meat from insect-fed chicken and supermarket as preferred place to shop (Harriet *et al*., 2019).

America

Domingues *et al*. (2020) investigated the willingness to accept insects as feed for poultry, cattle, pigs and fish of Brazilian consumers. They conducted four online surveys, one for each animal group. An acceptance of two-thirds of the respondents of insects as feed for fish was obtained, whereas half of the respondents did not favour insects as feed for poultry, cattle or pigs (Domingues *et al*., 2020). This seems to be surprising at first glance, since entomophagy has a vast tradition in Brazil (Costa-Neto, 2015). However, consumer studies have shown that most Brazilian consumers connect the consumption of insects with 'disgust' and 'no' (Cheung and Moraes, 2016) or perceive insects as unsafe (28%) or have no opinion on it (almost 50%) (Schardong *et al*., 2019).

Asia

Since entomophagy has tradition in a number of Asian countries (Yen, 2015), it was suggested that these so-called eastern cultures would be more accepting of insects as feed (Moon and Lee, 2015). None the less, the acceptance of insects as feed of the Asian consumers is an issue for farmers due to its potential impact on the desired market (Moon and Lee, 2015).

Australia

In Australia, insect-based feeds are currently fed to fish and poultry. It is assumed that consumers are more likely to adopt insects as feed than as food (DiGiacomo and Leury, 2019).

Europe

It is assumed that, since neither entomophagy nor the use of insects as feed has a tradition in Europe, there will be challenges in obtaining consumer acceptance, and as a result the number of studies on consumer acceptance is higher in comparison to other geographies.

Preferences concerning the attributes of feed (with and without insects) and of price (four attribute levels) concerning smoked trout fillets in France were investigated via choice experiments with and without information being provided in advance. While 60.5% of the participants agreed that it was natural for fish to eat insects, 15.3% considered trout fed with insects disgusting. Furthermore, it was observed that information about the environmental impact of fishmeal and about insect feed as an alternative positively impacts consumer choice. In addition, the price influences consumer choice significantly. For example, if the price of insect-fed trout is higher than conventional trout, 81.1% (non-informed) and 76.3% (informed) chose conventional trout. If the price of insect-fed trout is lower than conventional trout, 57.3% (non-informed) and 72.8% (informed) chose insect-fed trout (Bazoche and Poret, 2017).

In Spain on the other hand, consumers were willing to pay a premium price for gilthead seabream fed with either BSF or YM. When using insect as feed, the environmental impact of aquaculture was perceived as lower. This had a positive effect on WTP. Even though the Spanish consumers were willing to accept insect-fed fish, they had low taste expectations (Ferrer Llagostera *et al*., 2019).

Ankamah-Yeboah *et al*. (2018) investigated how insects as fish feed affect German consumers' purchase decisions. An online questionnaire revealed that the majority of the respondents were indifferent about the type of feed when buying fish. However, 23% of the respondents had negative attitude toward insect-fed fish. It was observed that the same group exhibited strong preferences for convenience. Convenience products could thus be a key for improved acceptance of insect-fed fish products in Germany.

The findings in France and Germany are in accordance with Popoff *et al*. (2017) who determined in a consumer study in the UK that the population largely lacks knowledge on feed and its environmental impact in general and insect feed in particular. They concluded that factors other than the nature of the feed impacted purchasing decisions and that information could improve acceptance of insects as feed. They also observed that only 10% of the respondents were opposed to Scottish salmon fed with fly larvae which was a lower number than in France (Bazoche and Poret, 2017) and Germany (Ankamah-Yeboah *et al*., 2018). Their results were similar to Mancuso *et al*. (2016) who also observed that 90% of all consumers interviewed had a positive attitude towards insects as feed. Nevertheless, it can be concluded that in all four studies acceptance was high. By contrast, a survey with Polish students resulted in lower acceptance of insects as feed. Around 60% of the respondents affirmed that they would eat poultry, pork, beef or fish that were fed with insects. Most of those were male and city dwellers (Orkusz *et al*., 2020). It is noteworthy that a consumer survey 3 years prior to this resulted in a lower acceptance level as compared to that reported in 2020 (Kostecka *et al*., 2017).

A comparison of the acceptance of insects as feed between Portuguese and Norwegian consumers revealed results that differed significantly with overall acceptance higher in Norway. Factors like disgust and acceptance of sushi had impacts on acceptance in both countries. Other factors impacting acceptance were different for Portugal (gender) and Norway (educational background, familiarity, convenience) (Neves, 2015). This shows that acceptance and marketing of insects as feed has to be regarded at a country level and cannot be generalized for globally or even on a European level.

Szendrő *et al.* (2020) determined in a consumer online survey in Hungary, that age, gender and income impact the willingness to consume animal products derived from insect-fed animals. Participants between 30 and 39 years, male participants and participants with a higher income are more willing to consume those products. This is in accordance with Laureati *et al.* (2016) who observed that age, gender, cultural background and food neophobia affect the willingness of Italian consumers to adopt insect-fed animal products.

In an online questionnaire with Dutch consumers, the acceptance of an insect burger, a chicken burger from insect-fed chicken, and a conventionally fed chicken burger were compared. It was observed that emotive messages were more effective in increasing consumer acceptance than cognitive messages for all burgers (Onwezen *et al.*, 2019). These findings are in accordance with Berger *et al.* (2018) who recommended hedonic over utilitarian claims for advertisement of insect-based food products. However, Onwezen *et al.* (2019) also determined that the respondents were more willing to accept a conventional chicken burger and an insect-fed chicken burger than an insect burger. This shows that acceptance of insects as food and insects as feed might not be comparable. These results are also in accordance with other European studies and suggest that the majority of consumers are likely to accept insects as feed for livestock and aquaculture more readily than as food.

Naranjo-Guevara *et al.* (2020) compared the acceptance of insects as feed and food of Dutch and German students. They observed that the willingness to accept insects as animal feed was higher than the acceptance of insects as food. This is in accordance with a consumer study where it was determined that so-called ‘insect-opposers’ showed a positive attitude towards insects as feed (Videbæk and Grunert, 2020). Corresponding to findings made by Neves (2015), it was also observed that national heritage seems to impact acceptance with 94% of the Dutch and 75% of the German respondents willing to accept insects as feed. Factors impacting the acceptance of insects as feed also included knowledge and information on benefits of insects as feed.

15.4 Sensory Analyses

It has been shown that taste of the resulting animal products also affects the acceptance of insects as feed (Popoff *et al.*, 2017; Ferrer Llagostera *et al.*, 2019). A number of sensory tests of meat and fish products from animals and fish fed with insects have been conducted, since feed and moreover the fatty acid composition of feed influence the fatty acid composition, aroma and flavour of animal products (Henry *et al.*, 2015) and taste is a key driver for food choices (Tan *et al.*, 2015).

A comparison of sensory analyses of animal products derived from animals fed with or without insect-containing feed usually showed no or only slight differences (Gasco *et al*., 2019a). Onsongo *et al*. (2018) determined that a replacement of soya bean meal and fishmeal with BSF meal of up to 55.5% crude protein did not affect aroma or taste of cooked breast meat of broilers. This was in accordance with results obtained by Pieterse *et al*. (2014) feeding up to 10% of HF meal and Altmann *et al*. (2020) replacing up to 75% of the soya bean meal with BSF meal. The latter found a lower adhesiveness of the meat, however. In addition, sensory profiles from breast meat of quail fed up to 15% defatted BSF meal were unaltered (Cullere *et al*., 2018). Moreover, consumer acceptance of rabbits fed with insect oil instead of soya bean oil was not affected by the altered diet (Gasco *et al*., 2019b).

No deterioration of the sensory profile of quail eggs was observed after feeding laying quail with BSF meal (Dalle Zotte *et al*., 2019). This was in accordance with Bejaei and Cheng (2020) who revealed in their study no change in odour, flavour and texture perceptions of eggs from laying hens fed with and without BSF meal.

However, a rainbow trout diet with up to 50% inclusion of BSF meal revealed that the diets significantly impacted the sensory profile of the fillets. Differences in aroma, flavour and texture were detected by trained panellists. With increasing insect meal inclusion, a metallic flavour increased and fibrousness decreased (Borgogno *et al*., 2017). This was opposed to findings made by Sealey *et al*. (2011) where untrained panellists found no significant differences between rainbow trout fed without or with insects, when up to 50% of the fishmeal had been replaced by insect meal. This implies that the training of the panellists impacts the resulting sensory analyses.

It appears that the degree of inclusion of insects in the diet of fish and animals impacts sensory acceptability. In addition, the actual inclusion of insect meal in the different studies is difficult to compare since it is sometimes not based on crude protein but on soya bean or fishmeal replacement. Usually, there are other protein sources such as wheat and maize (corn) in the feed. However, it can be concluded that an inclusion of insect meal in feed up to a certain threshold does not alter the sensory profile of the animal products. Since taste and taste expectations are fundamental to consumer acceptance, the maximum inclusion of insect meal has to be determined based on diet composition, animal species and product (egg, meat, fish). Generally, the taste of animal product fed with insects does not seem to be a barrier for consumer acceptance.

15.5 Conclusions

It can be concluded that the number of studies on acceptance of stakeholders of insects as feed for livestock and fish is limited and that this might be due to existing tradition and practice, as well as a general lack of consumer awareness of what animal feeds typically contain. It also appears that, on the whole, stakeholders do not deem it necessary to conduct consumer research. They are still struggling with legal and/or technical hurdles such as upscaling and cost reduction of the production process. To date, globally, insect production is still too labour intensive and mostly done at small scale. It has been suggested that the challenges the insect food and feed industry face can only be overcome if all stakeholders cooperate (van Huis, 2020). The acceptance of livestock and aquaculture producers largely depends on price in comparison to conventional feed, reliable supply of standardized quality, growth performance and taste of the animal products as well as acceptance by consumers. However, it is doubted that a sufficient supply of insect meal could be produced if demand increased at short notice.

At first glance, the number of studies on consumer acceptance of insects as feed appears to be low. However, an internet search has shown that studies on the acceptance of other feed ingredients are even scarcer. Therefore, by comparison the number of studies on the acceptance of insects as feed is not seen as a limitation. Existing studies indicate that consumer acceptance of insects as feed will most likely not be a barrier. These provide an array of factors that affect acceptance by consumers such as: (i) socio-demographic factors; (ii) price; (iii) knowledge and information on feed and insect production; (iv) food neophobia; (v) disgust and (vi) taste.

At the same time, it is clear that there is a gap in coherent consumer research at both regional and global levels. Factors that impact consumer acceptance of insects as feed should be researched at both regional and cross-country levels to gain insight into what drives consumers to accept or reject insects as feed. These studies would provide insights to support the development of strategies to address consumers' concerns and provide the groundwork for effective marketing to boost the insect feed sector.

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16 The Future of Animal Feeding

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16.1 Introduction

Today, feed producers face several significant global challenges to find suitable resources to produce compound feed for livestock, aquaculture and pets.

On the one hand, the growing demand for animal products, and thus for animal feed, associated with the need to find resources with reduced environmental impact, has led to the development of novel feed ingredients, and moves to decrease dependency on common resources, such as soya bean meal, maize and fishmeal. The current use of these resources is being criticized as unsustainable therefore driving the need for alternative ingredients to maintain the balance between food, feed and biofuel industries. Land degradation, water deprivation and drastic climate change are additional challenges impacting on livestock production, aquaculture and the pet food industry.

On the other hand, recent events have illustrated the need to reduce our dependency on imported resources, specifically from other continents, strengthened by consumer opinion exerting pressure to provide more ‘natural’ food production, for humans, livestock and pets. Accordingly, the development of novel sustainable raw materials plus improved efficiency of resource use, are playing, and will continue to play, a vital role in ensuring the sustainability of feed manufacture.

Significant relevance is now placed on the development of novel feed resources based on environmentally friendly approaches, circular economy solutions, and the use of natural resources. However, it is not likely, in the near future, to be feasible to completely replace existing feed ingredients with novel ones, leading to a focus in the sector on improving efficient use of existing ingredients thus decreasing demand.

Some novel feed ingredients have the significant advantage of making use of available agri-food co-products and producing them locally into novel nutrient sources. Insects are one such ingredient that have the capability to convert low-value vegetal co-products into a high-value nutritional solution, while also aligning with the environmental drivers that are prompting the feed revolution.

This chapter will provide an overview of the current knowledge on some existing novel feed ingredients besides insects, their potential impact on the quality of feed, and how they compare with insects. The chapter will also discuss major challenges to the use of insects as feed, focusing on what could be important in the future, as well as the need for further research and development.

16.2 Comparing Insects to Other Novel Feed Products

As well as insects, microalgae, former foodstuffs (co-products) and single cell protein (SCP) are all regarded as potential novel nutritional resources for animals.

Microalgae

Microalgae have been used for centuries as nutritional supplements for both humans and animals. Nevertheless, the commercial production of microalgae is relatively recent and of the 100,000 species that are believed to exist, no more than 30,000 have been studied, only a few hundred have been evaluated and just a handful are cultivated in industrial quantities (Chaumont, 1993; Radmer and Parker, 1994; Borowitzka, 1999; Olaizola, 2003).

Microalgae are an important aquatic resource. Whereas most microalgae are autotrophs, there are some heterotrophic organisms. Although microalgae are genetically a very heterogeneous group of organisms, with a wide diversity of physiological and biochemical characteristics, the most important phototrophic species are *Arthrospira* (formerly *Spirulina*, blue-green algae), *Chlorella*, *Dunaliella* and *Haematocussus* (Madeira *et al.*, 2017).

It is the ability of microalgae to photosynthesize that has promoted the development of increased research into the use of microalgae biomass as food and feed but also as biofuel, representing a potential substitute for conventional energy sources (Chew *et al.*, 2017). However, besides use as fuel, microalgae can also be cultivated for other valuable resources such as cosmetics, as well as supplements for animal feeding (Madeira *et al.*, 2017) (see Table 16.1).

Table 16.1. Comparison of novel feed ingredients.[a]

Feed ingredient	Main nutrients	Advantages	Challenges	Needed improvements	Other uses
Microalgae	Protein (all essential amino acids), polysaccharides and fatty acids (MUFAs and n-3 and n-6 PUFAs and high levels of both EPA and DHA)	Rich in n-3 LCPUFAs	Low cell-wall digestibility, high cost of processing (dewatering/drying)	Production and processing costs	Biofuel, cosmetics, pigments (carotenoids and chlorophylls)
Former foodstuff	Carbohydrates (sugar, starch), oil and energy	High energy content and relatively low cost per tonne	Possible packaging residues, low protein content, high oil content	Nutrient and moisture content consistency	Substrates for other novel food ingredients, anaerobic digestion
Single cell protein	Protein, vitamins and phospholipids	High growth rates and ability to use unique substrates	High nucleic acid content, high cost of production, legislation limitations	Production scale-up	Human food and supplements
Insect meal	Protein, oil, chitin	Can complement traditional protein sources and can grow on a wide variety of substrates	Cost of production, availability, legislation limitations	Standardization in growing procedures	Biofertlizer, additives (chitin and AMPs)

[a] AMPs, antimicrobial peptides; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; LCPUFAs, long-chain polyunsaturated fatty acids; MUFAs, monounsaturated fatty acids; PUFAs, polyunsaturated fatty acids.

The incorporation of microalgal biomass into animal feeds may provide vitamins, essential amino acids, and valuable fatty acids (FA), minerals and pigments (see Table 16.1)). This novel feed ingredient can be valuable in pets (dogs, cats and ornamental birds), horses as well as livestock (cattle, fish farming, pig and poultry feed). However, a thorough biochemical characterization is essential to enable the most suitable microalgae species to be used for specific feed technology applications, namely as supplements in novel animal diets (Batista *et al*., 2013).

Despite their wide range of applications and the availability of different species, the technology for the production of microalgae is still inefficient (Dassey and Theegala, 2013). Bioindustrial solutions can be used to balance overall production costs by taking advantage of all products with commercial interest that could be obtained from microalgae (Rawat *et al*., 2011). Moreover, eukaryotic microalgae have very recalcitrant cell walls that defy solubilization, and in addition anti-nutritional factors reduce diet efficiency by trapping valuable nutrients, thus preventing them from being digested. Therefore, it becomes imperative for the feed industry to develop adequate technologies to improve microalgal nutrient bioavailability in animals. While microalgae can be provided directly for ruminants, biomass processing is necessary prior to incorporation into monogastric feeds (Austic *et al*., 2013; Lum *et al*., 2013).

The nutritive value of microalgae for livestock production is highly variable. First, it depends on the species of microalga and its chemical composition (protein, lipids, polysaccharides, vitamins, antioxidants and minerals), and secondly, on the adaptation of the animal to the taste and smell of the ingredient (Madeira *et al*., 2017).

Protein is one of the main drivers of novel feed ingredient research. The high protein content of various microalgae species is a major factor that favours their utilization in livestock feed and as they are able to synthesize all amino acids, they are also a source of essential amino acids (Kovač *et al*., 2013). It has been claimed that the average quality of most microalgae protein fractions is equal to or even higher than conventional plant protein fractions (Becker, 2007).

Microalgae lipids are also an invaluable nutrient. In humans there is insufficient intake of n-3 long-chain (> C18) polyunsaturated FA (n-3 LCPUFA) that are beneficial to health, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), making these nutrients a dietary requirement, therefore raising interest for animal feed enrichment. As primary producers, many marine microalgae are rich in these bioactive compounds and are a promising source of n-3 LCPUFA (Adarme-Vega *et al*., 2012).

Several species of heterotrophic microalgae have been acknowledged as biofactories for commercial n-3 LCPUFA production. Particularly, where heterotrophic microalgae are well established as an alternative source of DHA, autotrophic microalgae have been used for EPA production. For instance, microalgae, such as *Schizochytrium limacinum*, contain a DHA percentage between 30% and 40% of total FA when cultivated heterotrophically, and *Phaeodactylum tricornutum* and *Nannochloropsis* sp. (autotrophic) have an EPA content of up to 39% of total FA (Adarme-Vega *et al*., 2012). These results surpass those in wild marine fish.

Microalgae are currently being produced worldwide, with the highest percentage of production being used for feed. They have provided satisfactory results in terms of productive performance, as a substitute for mineral-vitamin premixes as well as for improving meat colour and lowering total cholesterol content. Microalgae are a promising new feed resource to support future animal production needs as they can be produced in an environmentally friendly manner, based on the principles of natural ecosystems, where biomass can be recycled, reducing secondary pollution. Production costs, however, are higher than common animal feeds, but they represent an interesting alternative thanks to their ability to grow under alkaline and saline conditions that are unsuitable for most traditional crops. A limitation for larger scale production, for example in greenhouses, is that they require energy for heating and drying processes, which will have an impact on the environmental footprint (Murta *et al*., 2020).

In conclusion, although microalgae can be a feed resource with relatively high crude protein content, interest in their use is largely due to the presence of n-3 LCPUFA (EPA and DHA) (Tocher *et al*., 2019) and carotenoids (Xu *et al*., 2014; Shah *et al*., 2018). These high value nutrients may put the price of microalgae out of reach for conventional livestock feeds.

Former foodstuffs

According to the European Union (EU) Catalogue of Feed Materials (Regulation (EU) No 2017/1017) former foodstuffs are: foodstuffs, other than catering reflux, which were manufactured for human consumption in full compliance with the EU food law but which are no longer intended for human consumption for practical or logistical reasons or due to problems of manufacturing or packaging defects or other defects and which do not present any health risks when used as feed.

(European Commission, 2017, p. 3)

Former foodstuffs, as defined above, are an interesting feed alternative, allowing the reuse of nutrients that otherwise could be lost, supporting the principle of the circular economy. Former foodstuffs, potentially linked to food waste, are also linked with the challenges of food security, resource and environmental sustainability and climate change. From this perspective, recovering former foodstuffs has great potential. They are a viable option for feeding animals and historically, feeding co-products to livestock animals has been in practice in many parts of the world.

At a food manufacturing level, there are always unintentional and unavoidable food losses which prevent foodstuffs from reaching the human consumption market. A broken biscuit or an incorrectly shaped loaf of bread may have lost its value for human consumption because they do not meet commercial food standards, literally making them former foodstuffs. They do, however, still retain a significant nutritional value for animal feed purposes (EFFPA, 2019). Issues can occur at many different stages of production and distribution, such as products that reach the end of their shelf life or inappropriate quality parameters (size, texture, wrong package/label, etc.).

However, today the requirements for precision feeding, for example, as well as for enhanced feed security and animal productivity require increased compliance with heterogeneity of former foodstuffs, challenging their usefulness for animal feed (Murta *et al.*, 2020).

The main challenges associated with the use of former foodstuffs for animal feed are consistent supply, as well as consistent nutrient and moisture content. Nutrient content may vary greatly according to the different co-products that can be used, but, in general, they will have an appropriate composition with a suitable storage life. This is because of the high energy content in the form of sugars, oils and starch in products such as biscuits, bread, breakfast cereals, chocolate bars, pasta, savoury snacks and sweets.

As former foodstuffs generally consist of pre-consumer food products that can be collected in food production plants and distribution centres, they are routinely packaged and thus need to be unpacked before grinding. Grinding enables effective mixing and helps to optimize nutrient availability for livestock. Packaging must be guaranteed to be removed effectively before grinding (Murta *et al.*, 2020). Drying is also an option to enable better storage and standardize the dry matter of materials. Temperature and duration of drying depends on the specific raw material being treated. Ensiling is also a typical processing option for moist materials, as it allows for longer term preservation and protection of nutritional quality.

These novel feed resources are cheap and available, but variability and consistency prevent greater utilization in animal diets. Unpacked and dried former foodstuffs are sold in Europe at large scale, but the cost of the processing needed to transform them into added value ingredients determines whether the final product is attractive (Murta *et al.*, 2020). Use of former foodstuffs as feed will decrease landfill use, as well as cost and may also deliver new revenue streams. The major challenge of automation, and thus decreasing the costs of processing plus the animal health considerations of increasing digestibility and improving nutrient absorption, must all be addressed. To overcome these issues, processing techniques are needed to convert other by-products into safe, nutritious and value-added feed ingredients (Murta *et al.*, 2020). The use of these former foodstuffs as substrate for insect production could be a processing step in the use of former foodstuffs to improve consistency and protein content. This use may even enable less desirable co-products to be valorized and may also remove the need for complex, costly packaging removal.

Single cell protein (SCP)

SCP production has been successfully achieved using algae, fungi and bacteria. SCP has the potential to deliver multiple solutions through a myriad of products and production approaches. However, considerable research, development and particularly scale-up is still required (Jones *et al*., 2020).

Bacterial SCP strains can produce very high crude protein contents (> 80% weight) and essential amino acid values, along with vitamins, phospholipids and other functional compounds, and can also utilize a wide range of feedstocks (Ritala *et al*., 2017). Bacteria can grow very quickly, increasing their mass twofold every 20 min to 2 h dependent on the species. They can be grown on many different combinations of carbon (starch, sugars, petrochemical and gaseous hydrocarbons), nitrogenous (nitrates, ammonia, urea and ammonium salts) and mineral feedstuffs.

Yeasts and fungi have long histories as animal feed ingredients, particularly for terrestrial livestock and for direct human consumption. The most widely known species are *Saccharomyces cerevisiae*, various *Aspergillus* spp. and *Fusarium venenatum*, but other strains are attracting interest for protein replacement, such as *Candida utilis* and *Kluyveromyces marxianus*. In most cases though, the aim is to deliver additional benefits such as *Rhodotorula mucilaginosa* biomass exhibiting immunomodulation and antioxidant benefits, and *Yarrowia lipolytica* producing EPA (Jones *et al*., 2020).

Although, SCP protein is only currently used in a relatively small proportion of animal feed, the growing global demand for protein is likely to make SCP increasingly important (Boland *et al*., 2013). High growth rates and/or ability to utilize unique substrates, such as CO_2 or methane, result in processes which offer much higher efficiency and/or sustainability than is possible from traditional agriculture (Ritala *et al*., 2017).

The range of sources for SCP used in animal feed is broader than that approved for human consumption and is expanding. Products derived from fungi (including yeast) and bacteria which are on the register of feed additives are all in use or under development. The production steps generally include: (i) preparation of nutrient media, possibly from waste; (ii) cultivation, including solid state fermentation; (iii) separation and concentration of SCP, in some cases drying; and (iv) a final processing of SCP into ingredients and products (Ritala *et al*., 2017).

A major limitation to the use of SCP is their high nucleic acid (NA) content. High NA intake can result in the build up of uric acid which can be detrimental in long-term feeding. This would limit SCP use in diets for humans although higher levels are tolerated by monogastric animals (pigs and chickens) and ruminants (cattle, sheep and goats) which can metabolize this. However, there are chemical and mechanical methods available to reduce NA levels in SCP (Bellamy, 2020).

16.3 The Insect Position in the Novel Feed Ingredient World

There is growing interest regarding the use of insects as an alternative ingredient source for feed production. The use of alternative feed ingredients in animal diets can be optimized in terms of their nutritional characterization, their safety and technological quality, in order to achieve better performance, as well as facing the challenges of increased feed demand in volume as well as quality and sustainability factors.

Insects can supplement traditional feed sources such as soya, maize, grain and fishmeal, with several different species of insects considered for use as a partial or total substitute of traditional feed sources (Barroso *et al.*, 2014; Tran *et al.*, 2015; Veldkamp and Bosch, 2015; van Raamsdonk *et al.*, 2017). Many trials have been conducted with different animal species, both terrestrial and marine, with the challenges associated with the use of insects in these animals changing, dependent not only on the animal species being fed, but also on the insect species being used, and the rearing substrate on which it was grown. However, it has also been demonstrated that different organic substrates can be used to rear insects, such as black soldier fly (BSF), without significantly affecting its amino acid composition, the profile of which has been shown to be similar to that of fishmeal and soya bean meal (Barroso *et al.*, 2014; Hall *et al.*, 2018; Sprangers *et al.*, 2017). However, when considering fat and ash composition, both can differ substantially according to the rearing substrate (Pinotti *et al.*, 2019). Thus, insect nutritional and technological properties are linked to the species, rearing system adopted and especially to the substrate used (Pinotti *et al.*, 2019).

Therefore, insect production has not only to achieve economically viable production scale, but it must also be standardized, to obtain a steady production and uniform product. Standardization is key, not only in relation to a single production unit, but also between different producers. Insects as a feed resource would greatly benefit from standard quality and nutritional values when considering the same insect species and product. This would increase feed manufacturer trust in this novel feed ingredient. However, different insect producers may use different insect species and rearing substrates, as well as different production and processing techniques. This results in different products with different nutritional values and properties entering the market, which could hamper wider use in livestock feeds.

Nevertheless, as the insect-rearing industry is only in its infancy, in the future the production and processing of insects will tend to be more similar between operators, as different production processes and technologies attain relevance in the sector. One opportunity to increase standardization and quality of insect products might be technology transfer between companies, enabling rapid growth of this novel sector and allowing investors and new operators to enter the market without the need to invest in the development of processing technologies. Technology transfer from other companies and research institutes that have spent recent years in research and development (R&D) will have processes providing the most suitable solutions, avoiding the need for new producers to start from scratch, costing time and money, as well as decreasing the chances of success for new businesses.

16.4 Can Insect Products Complement Traditional

and Novel Feed Ingredients?

In comparison with other novel feed resources, insects are both a good protein source and a rich source of valuable FA (Matthäus *et al*., 2019). While the protein composition is highly suitable for most animal feeds, the FA composition may not be the most advantageous, for example for aquaculture. Thus, aquaculture feed is currently still dependent on fish oil and other marine products.

It has been shown that the use of different co-products to rear insects, such as those from the marine environment, can influence its FA composition, but the opportunity to complement insect products with other resources, such as other novel feed ingredients may be a better solution. Microalgae, besides being a good source of protein, are a very good source of FA, such as EPA and DHA, and so could be a good complement to insects in aquaculture feed. On the other hand, insects contain high levels of protein and fat, whereas former foodstuffs contain mainly high energy in the form of carbohydrates and fats; therefore, insect protein could be used to bolster the use of co-products as alternative feed ingredients for livestock production (Pinotti *et al*., 2019).

SCP could be used as a complement to insect protein in the formulation of novel feed to decrease the use of traditional and possibly less sustainable protein ingredients. As a whole from a circular economy point of view, several of these novel feed ingredients represent a way by which food value chain co-products and wastes can be converted into valuable nutritional solutions and thus may represent a more sustainable, or at least a more nutrient efficient, way to feed animals.

Nevertheless, it should be highlighted that we do not expect to observe a complete replacement of traditional feed ingredients in animal feed. As demand increases, we hope that novel feed ingredients would be able to complement traditional resources and thereby limit predicted increases in demand for conventional ingredients. Indeed, we hope that in the future many new feed formulas would include at least one, if not a range of novel feed ingredients.

When and why insects?

It has been estimated that food waste accounts for 23% of arable land, 24% of freshwater resources used for crop production (Kummu *et al*., 2012) and thus, it is relevant to evaluate the use of insects in feed from a circular economy point of view. Insect rearing can potentially be used to upgrade low-value organic food waste streams increasing the efficiency of natural resource use and animal production.

Several livestock production companies in the world operate vertically, producing feed for the animals, rearing and processing them before market. Co-products include manure and other animal and vegetable co-products as well as former foodstuffs. Insects could be an invaluable tool for such organizations, as they can provide a perfect link between nutrient loss in vegetable co-products, and the protein supplement needed for animal feed.

Thus, insects have a perfect spot in certain value chains, where, more than creating value, they contribute to natural resource use efficiency through nutrient bioconversion. This might be the greatest contribution of insects to the food value chain, as they have the capability to be integrated perfectly in present-day market chains, while also converting wastes and less desirable co-products into high-value nutrient resources. When applied with the right infrastructure, such systems could contribute to animal production efficiency, environmental sustainability and supply chain profitability. Furthermore, insects, as for other novel feed ingredients, offer the potential to decrease dependency upon foreign products and feed resource imports, creating new local products, and thus helping to shorten supply chains.

Insects, more than feed

It should be highlighted that using insects for feed production is not a goal in itself but can be an instrument to achieve goals in biowaste reduction and conversion, improving sustainability and optimizing the food value chain. Insects should be evaluated as a tool to increase the efficiency of resources use and to increase income, and thus, one must evaluate them beyond their nutrient value as a feed ingredient.

For example, BSF are a rich source of lipids which can be industrially extracted to obtain a pure oil with several different potential uses, from feed and food, to biodiesel and cosmetics. It has been shown that BSF fat could be a useful alternative for other commonly used fats with specific technological properties in common with palm and coconut oils, which are increasingly associated with negative environmental impacts. In particular, the melting and crystallization behaviour of BSF larval fat seems to allow replacement for traditional fats (Matthäus *et al*., 2019).

In addition, the insect exoskeleton can be processed to obtain chitin and chitosan, and its industrial-scale production could offer a potential source of prebiotic oligosaccharides for pet, animal and human nutrition (Song *et al*., 2018). Applications for chitin and chitosan go beyond nutrition, as chitosan is characterized by non-toxicity, biodegradability, film-forming capacity, antimicrobial and antioxidant properties and good barrier properties of packaging films against oxygen (Aider, 2010; Kong *et al*., 2010; Verlee *et al*., 2017). Thus, the potential for the use of insect-derived chitosan to produce biodegradable plastics is being evaluated for a range of applications ranging from agriculture to food packaging.

Chitin-derived products have also been shown to be toxic to plant pests and pathogens, inducing plant defences and stimulating the growth and activity of beneficial microbes. Chitin-based treatments augment and amplify the action of beneficial chitinolytic microbes (Sharp, 2013). Such properties prompted the development of novel crop fertilizer and crop protection products that can be used in conjunction with one of the main insect products, the insect frass. In natural conditions, it is well known that frass deposition on soil has a great impact on soil fertility due to its high nutrient and labile carbon content and, therefore several companies have already started to sell frass as a fertilizer (Houben *et al*., 2020).

16.5 Conclusions

Considering all these possibilities, insects must be recognized not only as a nutrient source but also as a tool. The value of insects can surpass the production of nutrients and the use of its co-products to increase its profitability. In fact, although not possible to be used in monogastric animal feed according to present EU legislation, in the near future insects could be used in manure and household waste treatment approaches, decreasing the environmental impact of livestock production and landfill volumes (Li *et al*., 2011; Surendra *et al*., 2016; van Raamsdonk *et al*., 2017). This approach opens a completely new opportunity for insect rearing, that is distinct from insect production for animal nutrition which must comply with safety and hygiene regulations.

Increased sustainability of animal and food production can be delivered through insect production, not only through the development of new feed resources but also by contributing to the reduction and conversion of wastes into novel raw materials for bioindustry and biorefinery approaches.

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CABI – who we are and what we do

INSECTS AS ANIMAL FEED

Edited by

Heidi Hall, Elaine Fitches and Rhonda Smith

The global drive towards sustainability and improved animal health means there is a greater need for development of novel functional ingredients for the feed industry. As the requirements for protein for livestock feed and human consumption grows, the use of insect products as animal feed has gained increasing attention.

Covering global production systems of insect protein, oil and chitin, as well as co-products from this industry, this book:

- Considers in-depth nutritional and safety aspects of insects for feed.
- Reviews suitability of insects as feed for different animal species and life stages.
- Examines current knowledge of the value of insect-rearing residues as biofertilizers for crop health.
- Identifies the challenges related to regulation, legislation, consumer perception and acceptance, and commercialization of insects.
- Provides interviews with established and early-stage innovative companies producing insect protein for feed.

Including a focus on practices such as waste valorization, this book takes a holistic look at how insects could contribute to the sustainability of livestock production on a global scale. Providing an up-to-date reference for research scientists, nutritionists, and veterinarians, as well as prospective insect farmers, it will also be of interest to those with a broader curiosity towards climate change, sustainability, and the circular economy.

Cover designed by Hanna Bjone