# Economic Viability of Insect Production for Feed and Food in Europe

Hilde van den Hoorn

**Propositions**

1. Insect production for feed needs cost-effective upscaling. (this thesis)
2. Insect production for food needs consumer acceptance. (this thesis)
3. The difficulty of publishing multidisciplinary research on emerging sectors opens doors for predatory journals.
4. Undervaluation of statistically insignificant or null results reduces credibility of academic research.
5. Forest green soaks up stories and pours out inspiration.
6. Atomic habits are the basis of a productive day.

Propositions belonging to the thesis, entitled

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# Economic Viability of Insect Production for Feed and Food in Europe

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**Thesis**

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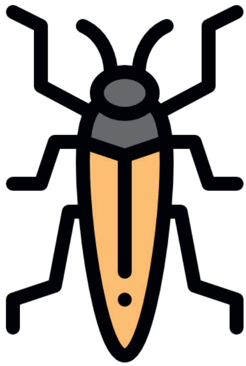

# 1

# General introduction

## 1.1 The emerging insect sector

The estimated expanding world population and concurrent necessity to reduce the environmental burden of food and livestock production systems require a transition from traditional to alternative protein sources for feed and food (Chia et al., 2019; Wood and Tavan, 2022). In addition to reducing conventional protein consumption as food (De Boer and Aiking, 2019), imported soybean and fishmeal used in animal feed needs to be replaced with alternative proteins (Chia et al., 2019). Insects and derived products have a high potential as alternative protein source for feed and food due to the insects' ability to convert low-value waste streams into high-value proteins, their low feed conversion rate and short life-cycle, and the minimal land-use requirements for production (Fasolin et al., 2019; Madau et al., 2020; Phi et al., 2020). While the production and consumption of insects have long been common practices in regions such as Southeast Asia, it is a challenge to establish large-scale insect production and consumption for feed and food in Europe (Raheem et al., 2019).

Insect production for feed and food is considered as an emerging sector in Europe (Delgado et al., 2022; IPIFF, 2020a). In the last decades, a high number of start-ups initiated the commercial production of insects for feed and food; currently the sector is dominated by small- and medium-scale businesses[1] (IPIFF, 2020b; IPIFF, 2021a). In 2021, the total production capacity of the sector was projected to reach one million tonnes of insect meal by 2030, with the main insect species produced being *H. illucens* (black soldier fly), *T. molitor* (yellow mealworm), and *A. domesticus* (house cricket)[2] (IPIFF, 2021a). Market research companies expected the value of the European market to increase from 46.75 to 826.76 USD million between 2021 and 2030 (Data Bridge Market Research, 2022).

The main stages of the insect supply chain involve the feed preparation[3], reproduction, production (rearing)[4], first stage processing, and further processing for feed or food purposes (Figure 1.1). The feed preparation involves for instance the mixing of different dry substrates, or the homogenising of wet side streams through blending. In the reproduction stage, beetles or flies (depending on the insect type) lay eggs which hatch into small larvae. These larvae are then fed and matured in the production stage until considered ready for harvest (Ojha et al., 2021). Under the current European regulations,

[1]Throughout this thesis the terms '(insect) farm' and '(insect) business' and 'insect producer' referring to a business producing insects are used interchangeably.
[2]Throughout this thesis both Latin and common names of the following insects are used interchangeably: *H. illucens* (black soldier fly), *A. diaperinus* (lesser mealworm), *T. molitor* (yellow mealworm), and *A. domesticus* (house cricket).
[3]Feed used for insect production is also referred to as 'substrate(s)'. The terms are used interchangeably in this thesis.
[4]In this thesis, the terms 'rearing', 'farming', and 'producing insects', all of which refer to the rearing of insects, are used interchangeably.

insects may be only fed with substrates of vegetable origin and a limited number of other materials from non-ruminants (IPIFF, n.d.a.; Lähteenmäki-Uutela et al., 2021). After harvesting, insects are commonly dried before further processing (Melgar-Lalanne et al., 2019). The main end products after further processing and extraction include insect meal, protein, fat (oil), and chitin (Ojha et al., 2021). A byproduct of insect production is insect frass, a mixture of excrements from reared insects, the feeding substrate, parts of insects, and dead eggs (IPIFF, 2021b). Insect frass has been suggested as a sustainable replacer of commercial fertilisers, but further evidence is needed to establish its agronomic value (Mannaa et al., 2023).

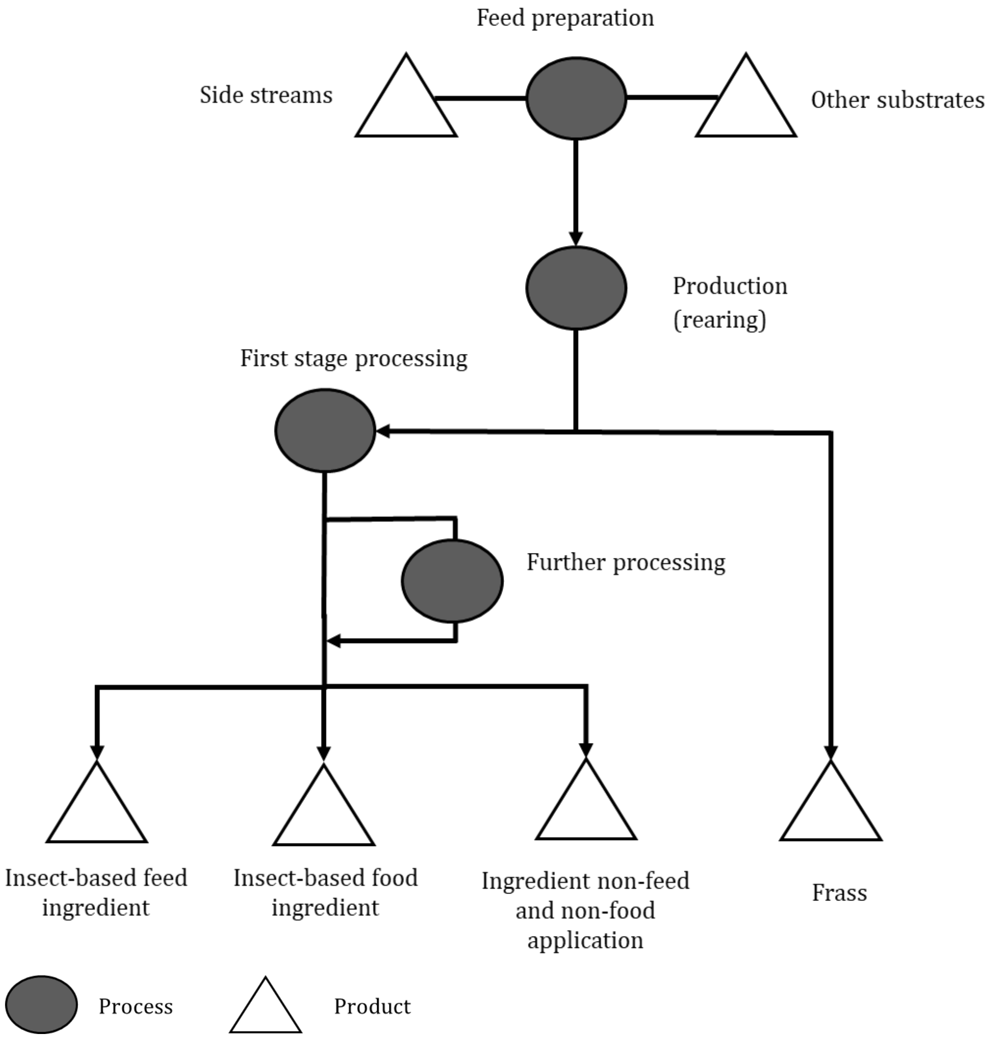


*Figure 1.1 An overview of the insect supply chain from feed preparation to marketable ingredient.*

In Europe, insect production and processing are destined for the feed and food market. The insect feed market is currently the main market in Europe (IPIFF, 2021a). Insects are produced for the pet food, aquaculture, poultry, and pig market, as well as other niche markets (IPIFF, 2021a). Within the existing regulatory framework, insect fats and Processed Animal Proteins (PAPs) of insect origin can be included in pet food formulations, as well as in feed formulations for aquaculture, poultry, and pigs (Meijer et al., 2023; Regulation (EC) No 1069; Regulation (EC) No 142/2011). The pet food market, currently having the largest share compared to other markets, is projected to constitute 40% of the total market share of insect meal for feed in 2025. Followed by the aquaculture market, which is expected to account for approximately 28% (IPIFF, 2021a). Even though the use of insects in pig and poultry feed formulations is recently allowed, introducing new opportunities for sector expansion, it is expected that the pet food and aquaculture market will remain the largest markets until 2030. Moreover, the aquafeed market is anticipated to outgrow the pet food market (IPIFF, 2021a; Rabobank, 2021).

In 2020, the insect for food sector consisted of micro-(81%), small-(16%), and medium-scale (3%) companies (IPIFF, 2020b). The majority of insect-based food operators exclusively covers the final processing step for food production (IPIFF, 2020b; Montanari et al., 2021). The insect-based food market is projected to grow rapidly to approximately 260,000 tonnes of insects in 2030 (IPIFF, 2020b). After initially focusing on national markets, producers are expected to increasingly shift their focus to European markets (IPIFF, 2020b). On the food market, insects are offered as whole insects, but are also incorporated in other food products (e.g. snacks, meat-like products, and bread), and in specialty food ingredients (e.g. sport powders and supplements) (IPIFF, 2020b). Since 2018, insect-based food products can only be sold after authorisation by the European Food Safety Authority (EFSA) (Lähteenmäki-Uutela et al., 2021). Successful authorisation of different processed insect species has taken place for use in food products since 2021. These include dried and frozen *L. migratoria*; dried, ground, and powdered *T. molitor*; dried, ground, frozen and partially defatted *A. domesticus*; and frozen and freeze-dried formulations of *A. diaperinus* (IPIFF, n.d.b.). The applicants of these authorisation requests hold benefit of market exclusivity for five years upon authorisation, after which the products get a generic status. The generics status allows other operators to produce approved insect products under similar conditions which can be freely marketed in the EU (IPIFF, n.d.b.).

Additional to the use of insects in feed and food, their use is also suggested in industrial (i.e. non-feed and non-food) applications such as cosmetic products and bioplastics. Furthermore, insects are found to be useful for biodegradation of plastics and for bioremediation (Van Huis, 2022).

This thesis focuses on the use of insects for feed and food.

## 1.2 Problem statement

The production of insects for feed and food offers promising business opportunities to contribute to a more sustainable form of livestock and protein production. Despite these potential benefits, businesses operating in this domain still encounter large challenges as they operate in highly dynamic environments (Van Huis, 2020). In the past decades, many small-scale businesses have been initiated by entrepreneurs and farmers who (partially) switched from conventional livestock to insect production (Hilkens et al., 2016; Weinreis et al., 2023). However, part of these businesses have experienced failure, for instance due to a lack of profitability (Madau et al., 2020; Thrastardottir et al., 2021). Madau et al. (2020) called for an investigation into cost and revenue structures of insect businesses for profitability improvement. The economic viability of small-scale insect businesses is essential as unprofitable operations or high risks discourage entrepreneurs from starting insect production, banks from providing finance, and value chain actors from investing (Hillier et al., 2016).

Upscaling insect production to large-scale businesses has often been suggested as a way to reduce cost-prices and subsequently increase the demand for insect-based feed and food products (Arru et al., 2019; Ortiz et al., 2016; Rabobank, 2021). Until now, high prices for insects are keeping feed and food producers from incorporating insects in their product formulations (Arru et al., 2019; Lombardi et al., 2019; Rabobank, 2021; Sogari et al., 2019; Tavares et al., 2022). To achieve successful upscaling, large-scale mechanisation and climate-controlled production require high-capital investments for which financing from banks or investors is needed (Rabobank, 2021). However, banks and investors face high risks when granting finance or investing in these insect businesses, primarily due to the sector's novelty and uncertain future consumer demands (Henchion et al., 2017; Rabobank, 2021).

Two primary problems are highlighted. First, the economic performance of small-scale insect businesses is insufficient and a lack of technical and economic data of insect producers limits benchmarking. Second, the economic viability of both small and larger insect businesses is uncertain due to the risks and uncertainties prevalent in this dynamic sector. A challenging impasse emerges; upscaling of the insect sector is necessary, but without finance for investments, this becomes difficult impeding upscaling and development of the sector.

## 1.3 Research gap

While profitability offers insights into the economic performance of a business, its economic viability presents a more holistic and comprehensive perspective (Savickiene et al., 2016). The economic viability of a business encompasses its capacity to survive and develop amidst current known and future unknown conditions, thereby serving as an important factor for business success (Savickienė and Miceikienė, 2021).

***Economic performance***

Due to the high potential of insect production for feed and food in Europe, research on insect production has been directed to the focal areas such as environmental sustainability of production (Smetana et al., 2021), technology developments for production (Ortiz et al., 2016; Sindermann et al., 2021), food safety of insects and derivatives (Van der Fels-Klerx et al., 2018), and consumer attitudes towards insect consumption (Sogari et al., 2022). The findings contributed, amongst others, to identifying the best insect species for mass production, optimising production conditions, and the development of production techniques. Whereas technical feasibility has been the main focus until now, the economic viability of insect production in Europe has not yet gained much attention, resulting in a lack of economic data for this specific sector (Madau et al., 2020; Mannaa et al., 2023; Van Huis et al., 2021). Prior studies presented data on market prices and production costs, see e.g. Llagostera et al. (2019) and Mancuso et al. (2019). Some economic data are also documented in the so-called 'grey literature', see e.g. Hilkens et al. (2016) and Rabobank (2021). Beyond Europe, large-scale insect production across other continents, such as Africa and Asia, is also gaining attention. While small-scale insect production is relatively widespread in these continents (Durst and Hanboonsong, 2015; Raheem et al., 2019), the literature on the profitability of insect production in these regions remains limited as well. Some studies have highlighted sales prices and predicted production costs, but concurrently indicated that the information on total costs and profitability remains scarce (Ssepuuya et al., 2017; Tanga et al., 2021).

Profitability is a main component in assessing a business's economic performance (Schuhbauer and Sumaila, 2016). To understand a business's profitability and its related indicators, a comprehensive examination of economic data encompassing fixed and variable costs, along with the initial production investments, becomes imperative (Tey and Brindal, 2015). However, the current absence of these data in standard accountancy databases, especially in emerging sectors such as the insect sector, necessitates for a thorough review of existing literature and execution of empirical business research.

***Risks***

Agricultural businesses are generally exposed to high risks, impacting their economic viability (Lezoche et al., 2020). Understanding the risks faced by insect producers and other actors in the supply chain is important, as it provides relevant information for assessing the economic viability of insect production (Ali et al., 2017).

Previous research identified the lack of knowledge for optimal operations and the high labour costs as important risks for insect production (Doberman et al., 2017). Yang and Cooke (2020) corroborated these risks and further mentioned high input costs, marketing challenges, and regulatory uncertainties as hurdles for upscaling insect production. In general, studies on the European insect sector focussed on individual risk domains, mostly related to technical feasibility of production, see e.g. Marberg et al. (2017), Meyer et al. (2021), Ribeiro et al. (2018), Vandeweyer et al. (2021), and Van Huis (2017). Insights into multidomain risks and risk management strategies of actors in the European insect supply chain remain scarce due to a lack of available data for this emerging sector.

Concurrently studying perceived risks across different domains and supply chain stages is relevant for insect producers and other supply chain actors. Hence, this serves all actors in implementing risk management strategies aimed at mitigating prioritised risks, aspiring to remain economically viable (Komarek et al., 2020; Nadezda et al., 2017). Additionally, established risk profiles serve as important sources for financers in decision-making on credit provision (Bosma et al., 2018). It is, however, not only crucial to gain insights into future risks, but also to learn how past barriers have impacted economic performance of businesses until now (Leonidou, 2004). Both dimensions, the past and future, provide insights into the dynamics of perceived risks. Hence, dynamic risk perception contributes to prioritising risks and risk management strategies in the design and implementation of (government) interventions. Synthesising knowledge on (dynamic) risks with insights into applied risk management strategies further contributes to insights in the performance of businesses, in particular for smaller companies and dynamic sectors (Dvorsky et al., 2021).

***Business models***

While risks are commonly estimated as the probability of events to happen, uncertainties describe the cases where the probability is not known (Hardaker et al., 2015; Teece et al., 2016). Uncertainties often stem from the business's external environment, where businesses typically have little to no influence on the probability of the events to happen (Chavas, 2018; Teece et al., 2016). Uncertainties such as market developments, technology advancements, and regulatory changes can impact businesses and their structure (Täuscher and Abdelkafi, 2018). Businesses need to be agile and ready to change their business models in short terms to remain economically viable (Teece et al., 2016). Due to the unknown probability of events, businesses cannot take preventive measures to mitigate the impact of uncertainties. Instead, their business models need to be robust, that is to remain technically feasible and economically viable in different uncertain scenarios (Haaker et al., 2017).

Studies exploring and structurally assessing business models for the insect sector are scarce. Prior studies examined for instance the circularity of different insect business models (Madau et al., 2020; Phi et al., 2020). Madau et al. (2020) concluded in their study that the production stage plays a key role in making the insect supply chain circular. In addition, Saatkamp et al. (2022) discussed the risks and opportunities of insect-fed poultry production, and also elaborated on the implications of these for sustainable business model development. They reasoned that business models in the insect-fed poultry value chain face asymmetric trade-offs in the opportunities upstream and risks more downstream the chain. Given the prospects of insect production for feed and food in Europe and the concurrent uncertain environments insect businesses operate in, insights into business models and their robustness are needed. The identification and assessment of business models add a business perspective to the previously documented technical knowledge, see e.g. Smetana et al. (2021) and Veldkamp et al. (2021). They further shed light on the relative robustness of different business models providing insights into the economic viability of insect business models for the future. These will guide business operators and policy makers in further developing the insect sector for feed and food in Europe.

To summarise, the knowledge gaps for this thesis are the following. First, the economic performance of insect businesses is scarcely studied resulting in a lack of data for the sector. Second, a lack of detailed and quantitative research into business risks and risk management strategies hinders the establishment of a risk profile for insect businesses. Third, there is a need for structural assessment of business models in the face of the fast developing and uncertain environments insect businesses operate in.

## 1.4 Aim of the thesis

The overall objective of this thesis is

*to assess the economic viability of insect production for feed and food in Europe.*

Specific research objectives (RO) are:

RO1 To review the profitability of insect production for feed and food.

RO2 To analyse the profitability of insect production in the Netherlands.

RO3 To assess past barriers, future risks, and risk management strategies in European insect supply chains.

RO4 To assess the robustness of three potential business models for insect production for feed and food in Europe.

The objectives RO1 to RO4 are answered in shown order in Chapters 2 to 5.

## 1.5 Contributions

This thesis contributes first by addressing the economic performance of small-scale insect producers by providing a comprehensive assessment of their previously undocumented costs, revenues, and investments. Second, it establishes a risk profile for multiple actors in the insect supply chain including the development of risk perceptions over time. Third, it provides an exploration and robustness assessment of three potential business models for upscaling insect production in Europe.

## 1.6 Conceptual framework

The economic viability of a business is defined as its ability to maintain economic performance both in current known and in future unknown (economic) conditions (Savickienė and Miceikienė, 2021). In understanding economic viability, insights are needed into operations, investments, and finance options of a business (Hillier et al., 2016) (Figure 1.2). Chapters 2 and 3 focus on the operational and investments aspects of insect businesses. Chapter 2 reviews documented economic data on costs and revenues related to operations, hereby addressing the economic operational performance of insect businesses. Chapter 3 empirically assesses economic performance of small-scale insect producers through technical and economic data on operations and investments.

Chapters 4 and 5 broaden the scope by assessing risks and uncertainties for insect businesses (Figure 1.2). All three components of economic viability are susceptible to risks (Teece et al., 2016). Insect producers face risks that affect their economic viability as an entity. In addition, it is important to recognise that risks encountered by actors downstream the supply chain can also influence the economic viability of producers. Risk management strategies are implemented to address the identified risks; however, these strategies often entail costs. Consequently, the choice whether to implement risk management strategies impacts economic viability. Chapter 4 assesses the impact of risks on the performance of insect businesses in the supply chain as well as the application of risk management strategies by supply chain actors.

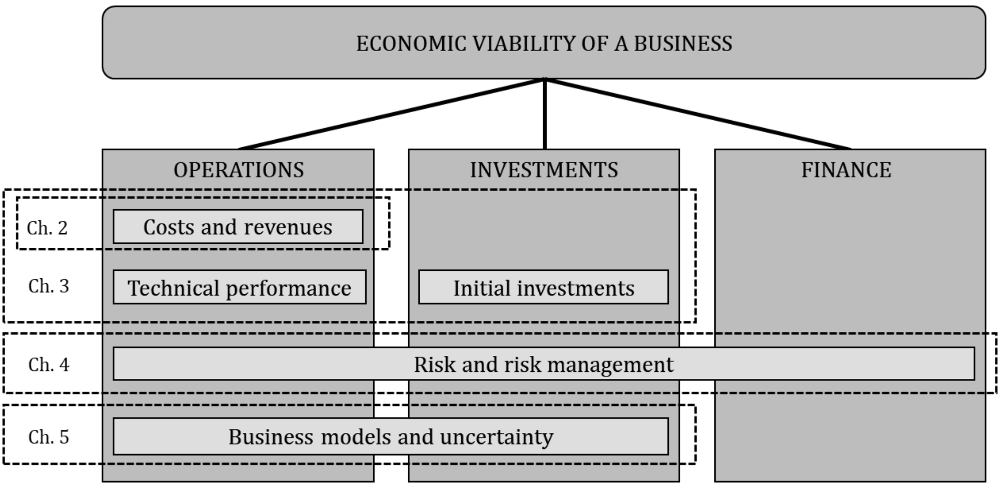


*Figure 1.2 The conceptual framework used in this thesis, centered around the main theme of economic viability. Ch. refers to chapter.*

While risks have a perceived (or otherwise quantified) probability and impact, uncertainties lack such quantifiable properties (Teece et al., 2016). Uncertainties underscore the need for robust business models. Chapter 5 studies the robustness of business models for insect production for feed and food in Europe. The chapter focusses on business models covering the stages from (re)production to the production of final ingredients for feed and food. It assesses the impact of future uncertainties for operations and investments of insect businesses, thereby giving insights into their robustness and long-term economic viability.

### 1.7 Thesis outline

This thesis consists of six chapters: the General introduction (Chapter 1), two chapters addressing the economic performance of insect production (Chapters 2 and 3), one chapter focusing on perceived risks of insect supply chain actors which could impact their economic viability (Chapter 4), one chapter exploring three business models and their robustness (Chapter 5), and eventually a General discussion (Chapter 6). Table 1.1 provides an overview of the study approaches and methods used in this thesis. It also shows which geographical location, supply chain stages, and insect species are considered in these studies (Chapters 2-5).

Chapter 2 establishes an overview of available (business) economic data underlying the profitability of insect production. It investigates available economic data on costs and revenues for insect production for feed and food in Europe. It summarises the literature and presents a state-of-the-art overview of insect production across Europe, and to a limited extent, beyond its borders.

Chapter 3 obtains economic data from existing businesses; it empirically assesses the profitability of *T. molitor* production in the Netherlands through investment appraisal. Assessed technical and economic variables are based on those commonly used for other livestock sectors and adjusted to the insect sector (Blanken et al., 2021; Veldkamp et al., 2021). Technical variables focus on production quantity and efficiency, while economic variables encompass initial investments, total revenues, and non-allocated and variable costs. These economic data are used to compute the gross margin and the net present value.

Chapter 4 assesses stakeholders' perceived past barriers and future risks for business performance of actors across the European insect supply chain. An online survey is conducted among stakeholders from four stages of the chain: rearing, processing, insect-based feed production, and insect-based food production. The survey assesses past barriers and future risks for four domains: (1) operations, (2) financial, cost, and market, (3) worker and food safety, and (4) regulations. Additionally, Chapter 4 investigates the risk management strategies implemented by stakeholders. The chapter further depicts the average perceptions of past barriers and future risks, along with the frequency of implementation of risk management strategies by using descriptive statistics. Moreover, inferential statistics are used to test for significant differences between perceived barriers and risks, shedding light on the development of these perceptions over time.

Chapter 5 builds on obtained results of Chapters 3 and 4 by exploring three business models for insect production and assessing their robustness through the Business Model Stress Test (Haaker et al., 2017). Experts are first asked to describe business models following the Business Model Canvas approach and to identify potential future uncertainties and scenarios for insect businesses following the PESTLE framework (Perera, 2017). The resulting business models and uncertainties feed into the robustness assessment of these models. In this assessment, the impact of scenarios on nine business model components is rated by experts following a four-colour model (Haaker et al., 2017). The assessment is conducted in four focus group sessions with stakeholders (n=23) from six European countries. Focus group sessions' outcomes are summarised in so-called heat maps, showing the estimated robustness of business models. The heat maps, together with the elaboration given during the focus group sessions, allow for a deeper understanding and explanation of the relative robustness of business models.

*Table 1.1 Overview of study approaches and methods used in this thesis.*

| **Chapter** | **Data collection** | **Method** | **Geographical location** | **Chain stages** | **Insect species** |
|---|---|---|---|---|---|
| Chapter 2: Profitability of insect production | Structured literature review | Profitability analysis | Global (with a main focus on Europe) | Rearing, first stage processing | *H. illucens, T. molitor, A. diaperinus, A. domesticus* |
| Chapter 3: Profitability of *T. molitor* producers | Structured farm interviews (n=7) | - Descriptive statistics<br>- Investment appraisal | The Netherlands | Rearing | *T. molitor* |
| Chapter 4: Barriers, risks, and risk management strategies | Online stakeholder survey (rearing (n=23), processing (n=8), insect-based feed production (n=14), insect-based food production (n=12)) | - Descriptive statistics<br>- Inferential statistics | Europe | Rearing, processing, insect-based feed production, insect-based food production | *H. illucens, T. molitor, A. diaperinus, A. domesticus* |
| Chapter 5: Robustness of business models | Expert elicitation (n=9), four focus groups (n=23) | Business Model Stress Test | Belgium, Germany, Spain, Italy, the Netherlands, Portugal, Switzerland | Rearing, processing, insect-based feed production, insect-based food production | *H. illucens, T. molitor* |

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# 2

# A review on the profitability of insect production

This chapter is based on the paper: Niyonsaba, H.H., Höhler, J., Kooistra, J., Van der Fels-Klerx, H.J., Meuwissen, M.P.M., 2021. Profitability of insect farms. *Journal of Insects as Food and Feed,* 7(5), 923-934. https://doi.org/10.3920/JIFF2020.0087

**Abstract**

Despite growing interest from entrepreneurs, knowledge on the profitability of insect production for feed and food is scarce. Insights into the economic figures of insect production are needed for farmers aiming to start insect farms, for banks seeking to provide financing, and for governments planning policy interventions. This review provides an overview of the profitability and underlying economic figures relating to the production of *H. illucens*, *A. diaperinus*, *T. molitor*, and *A. domesticus*. To enhance data interpretation, we also provide a brief overview of the global insect sector, with specific attention to farm-level operational practices. Sales prices refer to fresh larvae, dried larvae, or larvae meal, while operational costs include costs for feed, labour, electricity, water, and gas. Operational cost components differ per insect species, and therefore the relevant margins are specified for three insect species. The energy, feed, and labour margin for production of *H. illucens* ranges from 798 EUR to 15,576 EUR/tonne of dried larvae. The feed and labour margin for production *of T. molitor* ranges from 7,620 EUR to 13,770 EUR/tonne of fresh larvae. For production of *A. domesticus* the feed margin ranges from 12,268 EUR to 78,676 EUR/tonne of larvae meal. The margin range *for A. diaperinus* cannot be estimated, due to a lack of data in the literature. The ranges mainly reflect the differences in sales prices, which are found to depend on the geographical market location, type of market (feed or food), and quantity sold. Major operational costs include feed and labour, with feed costs varying substantially within and between insect species. The economic figures and margins presented in this chapter provide a foundation for the further development of the insect production sector.

**Keywords**: insect production; farm economics; sales prices; operational costs; *H. illucens*; *A. diaperinus*; *T. molitor*; *A. domesticus*

### 2.1 Introduction

The production of insects is promising from the perspective of food security and sustainability (Aiking and De Boer, 2019), and it is believed that insects can partly fill the projected protein gap (Henchion et al., 2017). For entrepreneurs to start producing insects, however, insights are needed into the profitability and underlying economic figures of insect production. If it is not profitable, entrepreneurs will not start insect production, banks will not be eager to provide financing, and actors within the value chain will hesitate to invest (Hillier et al., 2016). Government officials and scientists also need insights into farm costs and margins for policy interventions and further empirical research.

The insect sector distinguishes itself from existing agricultural sectors by its young and dynamic nature, and the proliferation of small-scale farms[5] (Derrien and Boccuni, 2018; Marberg et al., 2017). Given that each insect species is unique, with specific production requirements, a species-specific approach is needed (Heckmann et al., 2019). The European insect sector is in a developmental stage. Although there are some large-scale businesses, the majority is still operating on a small scale (Mancuso et al., 2019). To date, most research has focused on the technical aspects of insect production, such as food safety and quality (Van der Fels-Klerx et al., 2018), nutritional values (Roos and Van Huis, 2017), production and processing practices (Rumpold and Schlüter, 2013), and environmental benefits (Oonincx, 2017). Nevertheless, knowledge concerning the profitability of insect production remains scarce.

This chapter intends to provide a comprehensive overview of the profitability of insect production and underlying economic figures. It includes an analysis of peer-reviewed articles and other literature on costs and prices involved in the production of the following insect species: *H. illucens* (black soldier fly), *T. molitor* (yellow mealworm), *A. diaperinus* (lesser mealworm), and *A. domesticus* (house cricket). These four species are amongst the species that have received the most interest within the context of insect production in the Western world in recent decades (Van Huis, 2020). To enhance data interpretation, Chapter 2.2 provides an overview of the current status of insect production globally, with specific attention to the European insect sector and its operational practices. We focus on the European context, due to its high potential for sustainable protein provision and its growing commercial insect industry (Aiking and De Boer, 2019). The literature search strategy and data processing approach are presented in Chapter 2.3, followed by the literature results (Chapter 2.4), including an overview of sales prices[6], operational costs, and estimated margin ranges for insect production. We present sales prices only for

[5]Due to scale differences in the insect sector the terms 'farms', 'companies' and 'businesses' are used interchangeably in this chapter.
[6]Sales prices refer to both output prices and retail prices.

products produced in compliance with EU legislative requirements or comparable, including results from China, Egypt, Kenya, and Thailand. For example, data from farms using human excreta as feed are excluded, as this practice is not allowed in the EU. Because the literature review is based on data that have been sourced in different ways, Chapter 2.4 also provides details on the research approach and context. The chapter ends with a discussion and conclusions (Chapter 2.5).

## 2.2 The global insect sector and European operational production practices

In some parts of the world, especially in the tropics, insects are caught in the wild and have been part of human diets for a long time (Marcucci, 2020). Since it became clear that insects could also be reared on larger scale to serve as a protein source for feed and food, commercial insect production has been receiving additional interest. Insects are already being produced commercially in many parts of the world, with regional variations in insect species, scale of production and farm types, as well as in insect-eating habits. For example, insects are commonly reared and consumed on both smaller and larger scales in Asia, Africa, and Latin America (Kelemu et al., 2015; Raheem et al., 2019). In the past decade, the number of businesses producing insects on a larger scale has been increasing in America and Europe as well, with the former focusing on *A. domesticus* and the latter mainly producing *H. illucens* and *T. molitor*. These Western insect businesses were largely initiated by entrepreneurial companies, many of which have obtained financial support through crowdfunding campaigns and large investors (Dossey et al., 2016). In addition, many small enterprises are selling their insect products in niche markets as specialty items (Macombe et al., 2019). The International Platform for Food and Feed (IPIFF), a non-profit organisation based in the EU, reports that its members have raised 600 million EUR for investments in insect production through September 2019, and that its members are already producing 6,000 tonnes of insects for food and feed each year. Production could reach up to five million tonnes by 2030 (IPIFF, 2019). It has been predicted that the global insect feed market will reach a value of USD 1.4 billion by 2024 (Research and Markets, 2019). In Europe, insects are produced mostly as a protein ingredient for fish feed and pet food, as these are the applications that are currently allowed under European law (Sogari et al., 2019). Expected relaxations in European legislation are likely to allow the incorporation of insect proteins in pig and chicken feed, thereby increasing both the demand for and the number of insect-based feeds. The current growth in the insect-feed market is accompanied by increased interest in the use of insects for food in Europe (IPIFF, 2020a). IPIFF (IPIFF, 2019) indicates that aquaculture absorbs more than half of the insect production. For the other market segments no data on market shares could be found.

To date, the majority of Western insect farms are quite small, with much less technology and mechanisation than other agricultural farms (Dossey et al., 2016). In terms of operations, European insect farms generally have two separate production units: one for the maintenance of breeding colonies and one for the production of larvae from the eggs (Halloran et al., 2018). Many insect farms also perform first stage processing after harvesting the insects by drying them. An additional unit is needed for farms that also capture maturing of insects (as is the case for *A. domesticus*). In general, the indoor nature of insect production presents an ideal opportunity for farms to specialise rather than doing all aspects of the insect production steps themselves (Dossey et al., 2016). There are roughly three different business set-ups for insect farms: (1) farms that purchase eggs or small larvae from a supplier and focus on the fattening and, if relevant, the further maturation of the larvae; (2) farms that cover the entire production process, from laying eggs to harvesting and the first stage processing (i.e. drying) of larvae; and (3) large-scale production facilities, which cover all steps of the production of insect larvae, as well as further processing steps (e.g. milling, de-fattening, and the fractioning of proteins or fats). This literature review focuses on insect production and the processing steps drying and milling, and not on further processing (i.e. de-fattening meal or fractioning of proteins or fats) for incorporation of insects into feed or food.

The material and machine inputs required for an insect farm depend on the level of mechanisation. Basic inputs include the plastic trays in which insects are reared and fed. Depending on the level of mechanisation, inputs can also include drying machines (Pleissner and Smetana, 2020), conveyor belts for internal transport, and continuous feeding systems (Ites et al., 2020). Operational inputs are divided into material input and labour. Within the category of material inputs, the feed for insects is generally regarded as a main component, given that the quality and composition of feed is expected to influence the growth of insects and the quality of the end product (Jensen et al., 2017). Furthermore, the production environment is a crucial factor for the survival and growth of insects (Rumpold and Schlüter, 2013). For this reason, the material inputs of insect farms also include the energy and water used for insect production, as well as for first stage and further processing (Ortiz et al., 2016). Another important operational input is labour, given the labour-intensive character of small-scale and largely non-mechanised insect farms in particular (Meuwissen, 2011). More specifically, the majority of the farms operate largely with manual production systems for the feeding, housing, harvesting, and cleaning of insects (Dobermann et al., 2017; Rumpold and Schlüter, 2013).

With regard to the output of insect farms, the main product types include small larvae, grown larvae, and mature insects. The processing formats for these products include fresh larvae and dried larvae; larger production facilities also produce insect meal. Additionally, insect frass is regarded an important output in terms of volume, but is not yet commercialised on the European market. Hence, the regulatory framework is fragmented' and often restricts insect farmers from upcycling insect frass to high quality fertiliser (IPIFF, 2020b).

## 2.3 Literature search strategy and approach

***Search strategy***

The literature search initially focused on peer-reviewed articles published in the period 2010–May 2020 in three databases: Scopus, CAB Abstracts, and Web of Science. Search strings were predefined and included the following: 'black soldier fly' OR '*Hermetia illucens,*' OR 'lesser mealworm' OR '*Alphitobius diaperinus*,' OR 'yellow mealworm' OR '*Tenebrio molitor*,' OR 'Cricket' OR '*A. domesticus*' AND 'feed OR food' AND 'financ*' OR 'econom*.' An additional constraint was added for *A. domesticus*: AND NOT 'bean.'

The articles obtained through the search were screened for relevance according to selection criteria. First, to be included, a paper had to contain relevant economic quantitative data (e.g. economic figures on operational costs or sales prices of insect production). Second, the production system investigated had to focus on the commercial production of insects for feed or food, and not for cosmetics or medicines. Third, the production processes addressed were required to comply with EU regulations, or at least fulfil similar conditions (e.g. insects should not be fed on human or animal waste streams). Fourth, the article had to be written in either English or Dutch. No limitation was set on the geographical area in which the study had been performed, as long as production circumstances were compatible with the European context.

Due to the relatively low number of hits from refereed databases, snowballing was used to identify additional resources. Snowballing implies using the references of retrieved papers to identify additional papers relevant to our study aims. The initial hits obtained from refereed databases and snowballing are listed in Table 2.1, and their data are discussed below. For *H. illucens*, six peer-reviewed articles and one report were included in the analysis. The search for *A. diaperinus* led to the inclusion of one report and two non-peer-reviewed articles. For *T. Molitor*, three peer-reviewed articles and one report were analysed. The search for *A. domesticus* led to the inclusion of five peer-reviewed articles and one market-analysis report.

*Table 2.1 Initial hits and final number of articles and other sources included.*

| | Insect species | | | |
|---|---|---|---|---|
| | *H. illucens* | *A. diaperinus* | *T. molitor* | *A. domesticus* |
| *Number of refereed articles after initial search* | | | | |
| **SCOPUS** | 57 | 6 | 24 | 32 |
| **CAB Abstracts** | 84 | 17 | 64 | 43 |
| (Overlap with SCOPUS) | 34 | 4 | 15 | 10 |
| **Web of science** | 58 | 8 | 31 | 18 |
| (Overlap with SCOPUS) | 42 | 5 | 18 | 15 |
| *Total number of unique articles* | 123 | 22 | 86 | 68 |
| *Number of refereed articles included* | 6 | 0 | 3 | 5 |
| *Number of other sources included* | 1 | 2 | 1 | 1 |

### *Processing retrieved data*

The economic structure of a business (e.g. an insect farm) can be divided into three main components: operations (with gross margin as a key figure), investments (for which capital expenditures are an important parameter) and financing in the form of debt and equity (Hillier et al., 2016). Given the scarcity of data on the capital costs of and sources of financing for actual insect farms, this review further focused on operational costs, with operational inputs divided into production related material costs and labour. Sales prices were specified for three processing formats, differing in dry matter contents of insect products: fresh larvae, dried larvae, and larvae meal. Also, the end market (i.e. feed, pet food, and human food) for each sales price was identified. Insect frass was not included in this review, since the use of insect frass as fertiliser on a commercial level is impeded by the lack of a harmonised EU regulatory framework (IPIFF, 2020b). All costs and sales prices were recalculated into euros, applying an exchange rate of 1/1.10 (EUR/USD), as retrieved on 28 May 2020 (Investing.com, 2020), and presented in EUR per tonne of product. If the costs and prices in an article were not expressed as EUR/tonne, we calculated these from the data given in the article. Margins for each insect species were calculated based on the sales prices and averages of operational costs per tonne of product across the references available.

For example, for each tonne of larvae, we used the following equation:

$$\textit{Margin per tonne of larvae} = \textit{sales price per tonne of larvae} - \textit{average operational costs per tonne of larvae} \quad (1.1)$$

Since sales prices differed considerably between end markets, while cost components were comparable within the different insect species, margins were calculated based on sales prices and average operational costs. Based on the availability of information on operational costs, three different margins were specified: energy, feed, and labour margin for production of dried *H. illucens* larvae, feed, and labour margin for production of fresh *T. molitor* larvae, and feed margin for production of *A. domesticus* meal. These margins were combined into a margin range for the different insect species, with the range mainly expressing the variety in sales prices related to different end markets.

## 2.4 Profitability of insect production

Economic figures for the production of *H. illucens*, *A. diaperinus*, *T. molitor*, and *A. domesticus* are presented in Tables 2.2–2.5. The sources are listed in these tables, along with their research contexts, including country, study method, underlying source of the economic figures and targeted end market (i.e. feed, pet food, or human food). All included studies were conducted in an experimental or normative modelling context. In other words, none of the studies presented factual data on operational costs from operating farms. With regard to sales prices, the process presented in most of the studies are based on retail prices or personal communications. In addition, most of the studies focused on topics other than economics. Sales prices were for instance primarily investigated within the context of feeding trials or consumer-acceptance studies. The economic figures presented in Tables 2.2–2.5 include sales prices for the various processing formats. Operational costs include feed, water, electricity, labour, and gas. In this section, we provide details on all four insect species, starting with sales prices, and followed by operational costs. Estimated margins and their ranges are presented in Table 2.6.

***Profitability of H. illucens production***

Economic figures for the production of *H. illucens* from the selected studies are presented in Table 2.2. Reported sales prices for dried *H. illucens* larvae vary considerably, ranging from 1,816 EUR to 18,900 EUR/tonne of product. All of these sales prices are based on retail prices from around 2018, but they differ according to the type of market in which they were sold. For example, the sales price for *H. illucens* larvae sold in small quantities for pet food (18,190 EUR/tonne of product) is very high, compared to the others in the same category. The authors described this price as not so realistic, compared to another sales price mentioned in the article and ascribed it to the small quantity sold (Ites et al., 2020). Sales prices for larvae meal range from 427 EUR to 5,091 EUR/tonne of product. Sales prices in Egypt and Kenya are low, which could be explained by the low operational costs in these countries. In one study (Llagostera et al., 2019), the authors explained a reduction in sales prices between 2016 and 2018 in terms of increased competition over time. Sales prices for fresh larvae (i.e. not dried or processed), ranging from 2,000 EUR to 3,000 EUR/tonne of product, are obtained from only one report (Hilkens et al., 2016). Contrary to reported observations, fresh larvae could be expected to have the lowest sales price, as they do not require additional processing steps. Only two articles reported on operational costs for dried *H. illucens* larvae. One study estimated costs for *H. illucens* production in Germany based on a hypothetical design for an insect production facility. The other study also suggested a hypothetical (modular) design system within the German context. The large differences between the two articles with regard to operational costs per tonne of product could be explained as follows. First, the costs per unit for water, electricity, and labour differ considerably. This could be related to the production volume, which is higher for the design with the lower operational costs per tonne of product. Second, the designs differ in terms of feed costs. Pleissner and Smetana (2020) reported that their low feed costs include only a fee that might possibly be charged for the treatment of food waste, in addition to transport and collection costs. In contrast, Ites et al. (2020) also accounted for the costs of the feed. Although the authors did not provide information on the quality of feed, it is known that the optimal conditions and type of food waste used to produce *H. illucens* have a major impact on factors that increase both profitability (e.g. the growing time of the larvae) and the quality of the product (Law and Wein, 2018).

*Table 2.2 Research context and economic figures for H. illucens production.*

| *Source* | *Research context* | | | *Price (EUR/tonne product)* | | | | *Costs (EUR/tonne product)* |
|---|---|---|---|---|---|---|---|---|
| | **Country** | **Study method** | **Underlying source of economic figures** | **End market** | **Dried larvae** | **Larvae meal** | **Fresh larvae** | |
| *Refereed literature* | | | | | | | | |
| **(Abdel-Tawwab et al., 2020)** | Egypt | Feeding trial to implement larvae meal | Local market prices 2020 | Feed | n/a | 427 | n/a | n/a |
| **(Chia et al., 2019)** | Kenya | Feeding trial to implement larvae meal | Local market prices 2019 | Feed | n/a | 464 | n/a | n/a |
| **(Ites et al., 2020)** | Germany | Modular system design and economic analysis of three different types of food wastes for insect production, applied to German conditions | Retail price Illucens GmbH (2018) | Pet food | 18,190* | n/a | n/a | n/a |
| | | | Estimated price based on hypothetical farm design (24.51 tonnes of dry larvae/year) | n/a | n/a | n/a | n/a | $1{,}760^{1}$;$317^{2}_{i}$; $1{,}274^{3}_{ii}$;$426^{4}_{iii}$ |
| | | | Retail price Illucens GmbH (2018) | Pet food | 6,500** | n/a | n/a | n/a |
| **(Llagostera et al., 2019)** | Spain | Discrete choice experiment to assess preferences of 215 Spanish consumers on the incorporation of insect meal into fish feed | Personal communication (2016) | n/a | n/a | 5,091 | n/a | n/a |
| | | | Personal communication Entomb AgroIndustrial Platform (2018) | n/a | n/a | 2,273 | n/a | n/a |
| **(Mancuso et al., 2019)** | Italy | SWOT analysis of 28 European insect companies | Personal communication with an EU company Nextalim | Feed | n/a | 2,000 | n/a | n/a |
| | | | Based on personal communication (Gasco, 2018) | n/a | 2,500 | n/a | n/a | n/a |
| **(Pleissner and Smetana, 2020)** | Germany | Economic feasibility analysis of hypothetical design for insect production | Retail market price (place and year n/a) | n/a | 1,816 | n/a | n/a | n/a |
| | | | Estimated price based on hypothetical farm design (1,092 tonnes of dried larvae per year) | n/a | n/a | n/a | n/a | $21^{1}$;$160^{2}_{iv}$; $126^{3}_{v}$; $135^{4}_{vi}$; $1009^{5}_{vii}$ |
| *Other* | | | | | | | | |
| **(Hilkens et al., 2016)** | Netherlands | Market-analysis report | Company data (Protix 2015) | Pet food | n/a | n/a | 2,000 – 3,000 | n/a |

Additional information: *Sold in small quantities; ** Sold in bigger quantities
Operational costs: $^{1}$Feed; $^{2}$Water; $^{3}$Electricity; $^{4}$Labour; $^{5}$Gas
Calculation basis: $^{i}$4.34 EUR/m3; $^{ii}$0.5 EUR/kWh$^{-1}$; $^{iii}$21.41 EUR/hour; $^{iv}$1.54 EUR/m$^{3}$; v0.034 EUR/kWh-1; $^{vi}$30.80 EUR/hour; $^{vii}$0.0528 EUR/kWh$^{-1}$

***Profitability of A. diaperinus production***

Economic figures for the production of *A. diaperinus* are presented in Table 2.3. The number of obtained articles is low, and the sales prices reported represent different processing formats. The three-fold price difference between fresh larvae and larvae meal could be explained by the higher dry matter content of meal as compared to fresh product. Moreover, additional processing steps are needed to produce larvae meal. The high sales price for freeze-dried *A. diaperinus* reported by Meuwissen (2011) was originally sourced from a website advertising such products as delicacies for human consumption, where they were likely sold in small quantities with a high standard of quality.

***Profitability of T. molitor production***

Economic figures for the production of *T. molitor* are presented in Table 2.4. Reported sales prices for *T. molitor larvae* range from 5,727 EUR to 97,000 EUR/tonne of product. The low sales prices originating from China could be explained by the well-developed market in China, where *T. molitor* is produced industrially for food and feed, for both domestic use and export (Llagostera et al., 2019). The low prices could also be related to economies of scale, as a larger production scale often implies a higher level of mechanisation and lower labour costs (Ortiz et al., 2016). The European retail price obtained from Ortiz et al. (2016) includes only dried *T. molitor* larvae produced for the human food market, possibly explaining the higher sales prices for Europe. A high sales price of 97,000 EUR/tonne of dried larvae could be explained by the high quality of the product sold in retail. Sales prices for fresh *T. molitor* larvae range from 10,850 EUR to 17,000 EUR/tonne of product. The price difference observed between 2011 (Meuwissen, 2011) and 2019 (Mancuso et al., 2019) might be related to the increasing competition and/or technical progress within the insect sector. The difference in sales prices from one source reported in Mancuso et al. (2019) is related to the processing format, as the larvae with higher sales prices are sold in frozen form. With regard to the operational costs for fresh *T. molitor*, only feed and labour costs could be obtained, and from only one report. The labour costs of 2,140 EUR/tonne of product mentioned in this report are comparatively high, and the author attributed them to the low level of mechanisation in insect production, which further implies low productivity (Meuwissen, 2011).

*Table 2.3 Research context and economic figures for A. diaperinus production.*

| *Source* | *Research context and set-up* | | | *Price (EUR/tonne product)* | | | | *Costs (EUR/tonne product)* |
|---|---|---|---|---|---|---|---|---|
| | **Country** | **Study method** | **Underlying source of economic figures** | **End market** | **Dried larvae** | **Larvae meal** | **Fresh larvae** | |
| *Other* | | | | | | | | |
| **(Hilkens et al., 2016)** | Netherlands | Market-analysis report | Company data (Proti-farm 2016) | Pet food | n/a | 15,000 | n/a | n/a |
| **(Meuwissen, 2011)** | Netherlands | Market-analysis report | Retail price (Netherlands, 2011) | Human food | 118,000[1] | n/a | n/a | n/a |
| | | Report on protein transition | Price analysis Worldbank 2011 | n/a | n/a | n/a | 4,750 | n/a |

Processing format: [1]Freeze-dried

*Table 2.4 Research context and economic figures for T. molitor production.*

| *Source* | *Research context* | | | *Price (EUR/tonne of product)* | | | | *Costs (EUR/tonne product)* |
|---|---|---|---|---|---|---|---|---|
| | **Country** | **Study method** | **Underlying source of economic figures** | **End market** | **Dried larvae** | **Larvae meal** | **Fresh larvae** | |
| *Refereed literature* | | | | | | | | |
| **(Mancuso et al., 2019)** | Italy | SWOT analysis of 28 European insect companies | Company data - Krecafeed (Proti-farm, 2019) | Pet food | n/a | n/a | 10,850 | n/a |
| | | | Company data - Krecafeed (Proti-farm, 2019) | n/a | n/a | n/a | 17,000[1] | n/a |
| **(Ortiz et al., 2016)** | European Union | Literature review | Retail prices of insects for food (2015) | Human food | 45,454 | n/a | n/a | n/a |
| | China | | | Human food | 5,727 | n/a | n/a | n/a |
| **(Rumpold and Schlüter, 2013)** | Germany | Literature review | Commercial website | Human food | 32,330[2] | n/a | n/a | n/a |
| *Other* | | | | | | | | |
| **(Meuwissen, 2011)** | Netherlands | Market-analysis report | Retail price (the Netherlands, 2011) | Human food | 97,000[1] | n/a | 15,800 | n/a |
| | | | (De Bakker and Dagevos, 2010) | n/a | n/a | n/a | n/a | 1,090[3]; 2,140[4] |

Processing format: [1]Frozen; [2]Freeze-dried
Operational costs: [3]Feed; [4]Labour

***Profitability of A. domesticus production***

Economic figures for the production of *A. domesticus* are presented in Table 2.5, consisting largely of sales prices for *A. domesticus* meal and fresh product. The only sales price available for dried product is high relative compared to the other processing formats. Sales prices for *A. domesticus* range from 18,182 EUR to 84,590 EUR/tonne of product. The lower prices are largely from Thailand, where operational costs are generally low. The Thai market for *A. domesticus* is also well-known and further developed. Remarkably, the sales prices obtained from Morales-Ramos et al. (2020), which originated from the United States of America, are quite high compared to those reported by Reverberi (2020) who also includes sales prices from this region. Morales-Ramos et al. (2020) noted that the costs presented in their study do not include the costs of labour or diet mixing. Three different articles presented sales prices for fresh *A. domesticus* sold in Thailand, ranging from 1,867 EUR to 3,952 EUR/tonne of product. The authors attributed this price range to price decreases over time due to increasing competition. In addition, prices are higher in rural areas than they are in urban areas, with differences between small- and large-scale farms.

With regard to operational costs, Morales-Ramos et al. (2020) investigated different feeding substrates for crickets and their associated feed costs, with an average of 5,914 EUR/tonne. Higher feed costs are not always reflected in higher prices. For example, the feeding substrate with the highest feed costs yields the lowest revenue. It should be noted, however, that the prices for four similar feed formulations are relatively low compared to a special type of formulation. No data could be found on operational costs other than feed. In a general comment, however, Morales-Ramos et al. (2020) noted that the costs of mass-production are high, due to the primitive production techniques that are used, which involve a high amount of labour. In addition, the production of *A. domesticus* requires expensive commercial feed substrates.

*Table 2.5 Research context and economic figures for A. domesticus production.*

| *Source* | *Research context* | | | | *Price (EUR/tonne product)* | | | *Costs (EUR/tonne product)* |
|---|---|---|---|---|---|---|---|---|
| | **Country** | **Study method** | **Underlying source of economic figures** | **End market** | **Dried insects** | **Insect meal** | **Fresh insects** | |
| *Refereed literature* | | | | | | | | |
| **(Halloran et al., 2016)** | Thailand | Assessment of actors in the cricket industry | Sales prices Thailand | Human food | n/a | 26,363 | 1,867-3,952 | n/a |
| **(Halloran et al., 2017)** | Thailand | Analysis impact of cricket farming on livelihood | Sales prices from five Northern provinces Thailand | Human food | n/a | n/a | 2,018-2,950 | n/a |
| **(Hanboon-song et al., 2013)** | Thailand | Review of primary and secondary interview data | Sales prices from Thailand | Human food | n/a | n/a | 2,363-3,272 | n/a |
| **(Morales-Ramos et al., 2020)** | United States of America | Feeding trial with different feed formulations | Average sales price of nine companies. Feed costs based on internet prices. | n/a | n/a | 84,590 | n/a | 5,914[1] |
| **(Reverberi, 2020)** | Canada | Review on the development of cricket farming | Cricket Farm Inc. | n/a | n/a | 18,182 | n/a | n/a |
| | United States of America | | Founder of Aspire Food Group. | n/a | n/a | 36,364 | n/a | n/a |
| | United States of America | | USA cricket farming consultant. | Human food | n/a | 30,000 | n/a | n/a |
| | Belgium | | Founder of the Belgian edible insect association. | n/a | 45,455 | n/a | n/a | n/a |
| *Other* | | | | | | | | |
| **(Meuwissen, 2011)** | Netherlands | Market-analysis report | Retail price (Netherlands, 2011) | Human food | 200,000[2] | n/a | n/a | n/a |

Additional information: *Operational costs are based on an average calculation of five different feed formulations.
Operational costs: [1]Feed
Processing format: [2]Freeze-dried

***Margins***

Based on the prices and average operational costs for *H. illucens, T. molitor* and *A. domesticus* production (Table 2.2–2.5), the margins are calculated and shown in Table 2.6 Due to the lack of economic figures on the operational costs of *A. diaperinus* production, it is not possible to calculate the margin for this insect species. The energy, feed, and labour margin for production of *H. illucens* is -798 EUR to 15,576 EUR/tonne of dried larvae. The feed and labour margin for production of *T. molitor* is 7,620 EUR to 13,770 EUR/tonne of fresh larvae. The feed margin for production of *A. domesticus* is 12,268 EUR to 78,676 EUR/tonne of larvae meal.

Since prices differ between the specified end markets, individual margins are calculated. The operational costs are composed of different components, as for *T. molitor* only feed and labour are included, and for *A. domesticus* production only feed. Regarding the prices, some prices (i.e. retail prices) refer to prices further along the supply chain, but are used as proxies for sales prices. Sales prices are highest for the food market, followed by pet food, and were lowest for (aqua)feed. Also, the size of outlet influences the price, as small sold quantities in niche markets result in higher prices. In addition, a difference is seen in prices between Western and non-Western countries.

*Table 2.6 Margins (Energy, feed, and labour - Labour and feed - Feed) specified per sales price and estimated margin ranges. Prices, costs, and ranges are in EUR/tonne of product.*

| | Targeted end market | Country or Region (prices) | Operational costs components | Sales price | Average operational costs | Margin | Margin range |
|---|---|---|---|---|---|---|---|
| ***H. illucens* (dried larvae)** | Pet food (small quantities) | Germany | Feed, water, electricity, labour, gas. | 18,190 | 2,614 | 15,576[1] | -798 – 15,576[i] |
| | Pet food (bigger quantities) | Germany | Feed, water, electricity, labour, gas | 6,500 | | 3,886[1] | |
| | n/a | European Union | Feed, water, electricity, labour, gas | 2,500 | | -114[1] | |
| | n/a | European Union | Feed, water, electricity, labour, gas | 1,816 | | -798[1] | |
| ***T. molitor* (fresh larvae)** | n/a | European Union | Feed, labour | 17,000 | 3,230 | 13,770[2] | 7,620 – 13,770[ii] |
| | Human food | Netherlands | Feed, labour | 15,800 | | 12,570[2] | |
| | Pet food | European Union | Feed, labour | 10,850 | | 7,620[2] | |
| ***A. domesticus* (larvae meal)** | n/a | United States of America | Feed | 84,590 | 5,914 | 78,676[3] | 12,268 – 78,676[iii] |
| | n/a | United States of America | Feed | 45,455 | | 30,450[3] | |
| | n/a | United States of America | Feed | 30,000 | | 24,086[3] | |
| | n/a | Canada | Feed | 18,182 | | 12,268[3] | |

[1]Energy, feed, and labour margin; [2]Feed and labour margin; [3]Feed margin
[i]Energy, feed, and labour margin range; [ii]Feed and labour margin range; [iii]Feed margin range

## 2.5 Discussion and conclusions

This review aims to present current data on the profitability of insect production and an overview of the economic figures underlying its profitability. Before stating our conclusions, we discuss the interpretation and content of the economic figures.

First, the number of available sources from which unique economic data could be obtained is low. In many cases, data were cross-referenced, leading back to the same original sources. It is difficult to assess the reliability of some of these original sources, as they have been retrieved from commercial websites, reports, and other grey literature. To ensure the reliability of our overview, we have only included data from sources which presented original references for economic data.

Second, the research methods and set-ups used in the included studies are heterogenous, and mostly focus on topics other than economics. In particular, prices are investigated primarily within the context of feeding trials or consumer-acceptance studies, which present retail prices (and not sales prices). None of the studies includes factual farm data on operational costs. Such data are based predominantly on hypothetical designs (for *H.*

*illucens*) and placed within the context of experimental feed trials (for *A. domesticus*). For this reason, they do not necessarily reflect actual practices. These factors made it also difficult to translate the economic figures into margins. It is also important to note that, for actual farm set-ups, profitability entails more than sales prices and operational costs alone. Furthermore, it is necessary to consider capital expenditures and financing costs, neither of which is reported in any of the studies. Costs and prices may not necessarily reflect individual farms, instead they provide an overview of the available data ranges.

Third, the majority of the studies included in the review present only sales or retail prices. The use of retail prices is likely to result in an overestimation of margins. These prices differed for end markets too, with in general highest prices for human consumption followed by pet food, and feed. Also, the calculation of average operational costs across references was impeded by the scarcity of data on operational costs. For example, the average operational costs for *H. illucens* production could be calculated only based on data obtained from two sources, and only one source was available for *T. molitor* and *A. domesticus*. In addition, economic figures obtained for operational costs differed according to the species of insects. For *T. molitor* and *A. domesticus*, the literature provides information only on the costs of feed and/or labour, and not on any other material input costs (e.g. electricity, water, and gas). These differences in the operational cost items for different studies prevented us from comparing margin ranges across insect species. Therefore, we have calculated individual margins and presented the margins in ranges. The aforementioned considerations should be taken into account when interpreting these margins and their ranges.

Fourth, the prices and feed costs for *A. domesticus* meal are considerably higher than those for *H. illucens*, *A. diaperinus*, and *T. molitor* meal. This difference is in line with Brynning et al. (2020), who note that the prices of *A. diaperinus* and *T. molitor larvae* are lower than those of *A. domesticus*, which might be one of the reasons that they are more attractive for food and feed companies to include in their products. Remarkably, most of the economic figures obtained for *H. illucens*, *A. diaperinus*, and *T. molitor* are from Europe and China, while data from *A. domesticus* production originate from the United States of America and Thailand. In general, the literature included in the overview reflects a wide range of sales prices for comparable outputs (e.g. the same processing format for same insects), and they include several outliers.

Our findings on variations in sales prices are in line with the findings of Mancuso et al. (2019), who concluded that sales prices depend on many factors, including size of outlet, insect species, product type (larvae, adult, pupae), chain stage, and processing format. It is interesting to note that, with the exception of the article by Morales-Ramos et al. (2020), most of the studies included in this overview provided no information on the quality of feed and dry matter content, which is expected to influence the composition, and thus the value, of the product (Law and Wein, 2018).

In conclusion, this chapter provides an up-to-date overview of the profitability of insect production and its underlying economic figures. The margins are based on sales prices and average operational costs, expressed as margin ranges specified for three insect species. Energy, feed, and labour margin for *H. illucens* production, feed, and labour margin for *T. molitor* production, and feed margin for *A. domesticus* production are respectively: -798 EUR to 15,576 EUR/tonne of dried larvae, 7,620 EUR to 13,770 EUR/tonne of fresh larvae, and 12,268 EUR to 78,676 EUR/tonne of meal. Reliable margins for the production of *A. diaperinus* could not be calculated, due to a lack of economic figures on operational costs in the literature. Margin ranges cannot be compared between the different insect species, as they are calculated for different processing formats and include different cost components. The ranges of margins for all insect species are wide, which can be led back to the wide variety and differences in sales prices.

The reported sales prices depend on geographical location and type of market (i.e. feed, pet food or human consumption), as well as on the quantity sold in niche markets. Sales prices are relatively low in non-Western countries, as compared to those in Western countries, which might be related to inter alia lower operational costs in the former. Operational cost is, however, not the only component determining the sales price, as it is also dependent on, for example, the type of market sold and the size of outlet. In general, sales prices for products intended for food are higher than those for products intended for feed. This difference could be due to the higher quality required for food production and the small quantities sold. The price difference over time that has been observed for the production of *H. illucens* meal could be explained by an increase in competition or technical progress.

The amount of information available with regard to operational costs varies with species. For example, labour costs are subject to differences in the hourly fees applied. Considering the labour-intensive process of insect production, which is related to the low level of mechanisation on most insect farms, these labour costs are seen as an important cost component. Although we could not draw any conclusions on cost-reduction or profit increase of insect production, it has been suggested that increasing levels of mechanisation will reduce labour costs and that the use of low-value feed substrates will reduce operational costs. Regarding the sales of farm output, commercialisation of insect frass as fertiliser could provide an additional source of income for insect farmers. Additional research is nevertheless needed with regard to the additional costs and consequences of larger-scale production.

Further research on the profitability of insect farms is also highly recommended, in order to make a constructive contribution to the development of the insect sector and to increase the availability of economic data on insect production. The focus should be on collecting factual farm data, in order to establish an overview of the profitability of practicing farms. First, farm outlet prices are necessary to calculate a reliable gross margin for insect rearing companies. Second, the inclusion of capital expenditures and financing costs in the calculation of profitability would provide a more differentiated calculation at the company level. This would provide farmers with a more reliable source of data to consult when starting new farms, while helping and financial institutions and governments to facilitate access to financing and other services. Another valuable future contribution would be a clear overview of the different prices and costs associated with different geographical locations, which could be linked to different production systems. This could help to identify which production systems would be most suitable for which countries (e.g. in terms of the amount of labour needed).



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# 3

# Profitability of insect production for *T. molitor* farms in the Netherlands

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**Abstract**

Insects are increasingly considered as a relevant alternative protein source in the transition to a more circular economy and more sustainable food production. Understanding the profitability of insect farms is crucial for starting entrepreneurs, established rearers, and third parties. In this chapter we analysed the revenues and expenses of seven *T. molitor* farms in the Netherlands, representing approximately a quarter of the total sector. We calculated their gross margin and net present value. Revenues came from the sales of fresh larvae and insect frass, and from extension services. Expenses included investments, and non-allocated and variable expenses. Results cover technical and economic results, and a qualitative description of farm operations. The average gross margin and net present value were 1,185 EUR/tonne and –641 EUR/tonne fresh larvae production, respectively, but the economic results varied greatly between farms. The main elements of *T. molitor* farms' profitability included the sales price of larvae, and its labour and substrate expenses. Our estimates can be used by decision-making of farmers, credit providers, and policy makers to support the growth of this still very small, but emerging sector.

**Keywords**: insect farm profitability; economic viability; insect rearing; yellow mealworm production; *T. molitor* production.

## 3.1 Introduction

(Partial) replacement of traditional protein sources by insects or derivatives in feed and food is regarded as a potential contributor in the ongoing protein transition and pathway towards more sustainable use of resources (Fasolin et al., 2019). Whereas the production and consumption of insects has long been a common practice in regions such as Southeast Asia, it emerges to be a major challenge to establish this form of alternative production and consumption in Europe (Raheem et al., 2019). Positive developments have taken place and investments are on the rise in the European insect sector, but upscaling remains a challenge limiting development of the sector (Montanari et al., 2021; Rabobank, 2021). Previous studies concluded that the main causes of this challenge include the restrictive legislation on the one hand, but also the lack of financial resources for upscaling and stability of supply and demand of this growing industry on the other hand (Niyonsaba et al., 2023; Yang and Cooke, 2020).

Empirical research into the economic viability of the European insect industry is primarily limited to studies on the incorporation of insects and derivatives in feed and food products, see e.g. Arru et al., 2019, Maroušek et al., 2023, and Selaledi et al., 2020. We also indicated in Niyonsaba et al. 2023 that high prices of insects and derivatives limit their use as ingredients, and that regulatory barriers and a lack of demand for insect products impede profitable expansion. In Chapter 2, we provided a literature-based overview of farm economic data (Niyonsaba et al., 2021). We concluded that factual data on costs and revenues of operating insect farms are needed to evaluate the economic viability of farm businesses. In addition, these data aid in identifying financial risks, in adjusting potential business models to mitigate these risks, and in increasing the profitability of production (Euchner and Ganguly, 2014). Considering the dynamic nature of the insect sector in fast changing business environments, the call for insights into economic figures becomes even more urgent as it also supports the sector in gaining recognition and further professionalisation.

Empirical evidence on the economic viability of insect farms in Europe is not yet available. In this chapter we aim to analyse the profitability of *Tenebrio molitor (T. molitor)* farms in the Netherlands. The yellow mealworm – *T. molitor* – is regarded as an important species for (industrial) rearing of insects on the European market due the species' technical feasibility for upscaling and its inclusion in feed and food products. In this chapter, we first present an overview of farm operations and technical data. This is followed by an assessment of the revenues, non-allocated and variable expenses of *T. molitor* farms in the Netherlands, based on which the gross margin (GM) and net present value (NPV) are calculated. We contribute to the literature by providing first estimates on revenues and expenses of *T. molitor* production as a basis for future research into profitable forms of insect rearing in- and outside the Netherlands. More broadly, we contribute to economic research for this specific sector, which has been limited to date. Results can further guide service providers in decision-making on (credit) risk assessment as well as insect rearers in making investment decisions, benchmarking their position in the market, and adjusting their business model to increase profitability. In this way our results can help to upscale the production of alternative proteins.

## 3.2 Analytical framework and profitability calculations

Based on what is commonly used for other livestock sectors, we assessed variables adjusted to *T. molitor* farm operations, and complemented them with sector-specific variables (Blanken et al., 2021; Veldkamp et al., 2021). Technical farm data included labour requirements, feed inputs, and production volumes. Farm economic data included initial investments, total revenues, as well as non-allocated and variable expenses. Investments included total investments in buildings, installations, machinery, and other assets. Non-allocated expenses included rent for buildings as well as expenses for administration, marketing, and quality purposes. Variable expenses were related to labour, feed, utilities, and insect health (pest control and hygiene). The profitability of *T. molitor* farms in the Netherlands was assessed through the GM and NPV.

The $GM$ per tonne fresh larvae production in year $t$ ($GM_t$) was calculated by:

$$GM_t = TR_t - VE_t \tag{3.1}$$

Total revenues ($TR$) result from sales of fresh larvae and frass, and extension services. Variable expenses ($VE$) for the production of fresh larvae include labour, feed, utilities, and health expenses. Expenses for purchase of young larvae were not included in profitability calculations as most farms largely controlled the reproduction process themselves. Labour was accounted for under VE as the needs increase with production volumes. To account for unpaid labour, the average labour expenses per FTE[7] for hired labour have been used to estimate expenses for own and family labour.

The expected annual cash flow per tonne fresh larvae production in year $t$ ($CF_t$) is given by:

$$CF_t = TR_t - NE_t - VE_t \tag{3.2}$$

Where NE represents the non-allocated expenses for marketing, quality, and accounting purposes, and, if applicable, rent for the buildings. Maintenance, taxation, and insurance expenses for buildings, cars, and other equipment were not available.

[7]One FTE refers to one working week of 40 hours for 52 weeks in a year.

The NPV, then follows from:

$$NPV = -INV + \sum_{t=0}^{t=T} \frac{CF_t}{(1+r)^t} \tag{3.3}$$

Where $INV$ are the initial investments for buildings and installations, machinery, and other assets at $t = 0$, and $r$ is the discount factor. For farms that did not have investments for own buildings, only investments for machinery and other assets were considered in the calculation. The rent paid for the building was counted as an expense in $NE$. Cash outflows and inflows were assumed to be constant over time as the information available was insufficient to estimate future yields, sales prices, and expenses. A discount factor ($r$) of 10% was used to account for inflation, risk, and interest. The $NPV$ was calculated over an investment period of 20 years ($T$).



## 3.3 Materials and methods

***Data collection through structured interviews***

Farm economic data were collected through farm interviews as accountancy data were not available for small-scale *T. molitor* farms in the Netherlands. Through semi-structured interviews with *T. molitor* rearers operating in the Netherlands and producing for feed or food we obtained quantitative technical and economic farm data. A data collection sheet for rearers was predesigned by the two interviewing researchers based on literature (Blanken et al., 2021; Veldkamp et al., 2021). Three experts (two from research and one from the industry) reviewed the sheet prior to the data collection to ensure the correct interpretation of variables. The data collection sheet was designed in Dutch.

Contact details of potential participants were obtained via professional networks of the authors. Insect rearers (n=25) were invited via e-mail and afterwards contacted by phone to confirm participation. Ten rearers agreed to participate: three rearers focussed primarily on the reproduction and seven primarily on the rearing. Others did not respond to the invitations or indicated they “did not feel confident to participate”. Participants received a shortened version of the data collection sheet in preparation to the interview. The majority of the interviews were conducted on-site by two researchers, one as interviewer and one as notetaker. Consent was signed and a brief explanation on the procedure was given at the start of the interview. The interview then followed the structure of the data collection sheet, but if needed the order was adjusted. During the interviews, additional clarifying questions were posed where necessary. Questions which could not be answered were marked as unanswered.

***Data collection sheet for farm interviews***

The data collection sheet for farm interviews consisted of five parts. In the first part, rearers were asked to introduce their farm and share their vision on the Dutch *T. molitor* sector. The second part aimed to collect quantitative and qualitative information about the farm and its operations, mainly on the *activities carried out on the farm*, *amount of labour (hired and unpaid)* expressed in Full Time Equivalent (FTE), and annual *labour expenses.* The third part comprised questions on the technical details, revenues, and expenses related to the production of larvae, assessing first the *type* and *amount of feed* needed annually, the *length of one production round*, and the *volume of fresh larvae produced annually*. Furthermore, the *revenues from sales of fresh larvae* and *frass*, and additional offered *extension services*, i.e. education, consultancy, and research participation, were registered. In this part the annual expenses for *insect eggs or young larvae, dry and wet feed, insect health,* and *utilities* were assessed as well. In the fourth part of the data collection sheet, rearers were asked to list all *investments* in *buildings*, *machinery*, and *other assets*. If buildings were rented (not owned), the *annual rent* was recorded. In the fifth part, other expenses such as those related to *administration*, *marketing*, and *quality* as well as *car expenses* were collected. Rearers were also given the opportunity to add other expenses, if any, not included in those listed above.

***Data analysis***

For quantitative variables, the ranges (minimum and maximum values) were calculated. The technical and economic farm values, including the calculated GM and NPV, are presented in unit per tonne production. Averages could not be calculated due to the large heterogeneity across farms in the obtained data. Since farm-specific data cannot be displayed for anonymity reasons, the values have been categorised per variable which are displayed as frequency distributions in the form of histograms in the Supplementary material. This categorisation was only done for variables which were expressed in unit per tonne production to safeguard anonymous presentation of results. The total number of responses (sample numbers, n) differs per variable, as not all rearers could provide all the requested data. For one farm we could not calculate GM and NPV. Preliminary quantitative results (ranges of all technical and economic variables) were reviewed by one expert from research to ensure that no result could be traced back to a single mealworm farm. These preliminary results were then compiled and evaluated in a group discussion with six rearers (participants of this research) to verify whether the ranges are representative of actual practices. Additional qualitative information on farm operations and the insect sector were used for further interpretation of the data.

## 3.4 Results

In this section we show the technical and economic results. There is substantial variation between the farms in our sample, as illustrated by the minimum and maximum values. As both the insect sector in the Netherlands and the sample in our study are relatively small, it is difficult to elaborate on the exact reasons for these (at times) large differences without identifying a specific farm. We therefore discuss causes of variation in a more generic way.

***Technical results of T. molitor farms***

The mealworm farms in our sample (n = 7) produced between 28.60 and 62.40 tonne fresh larvae annually (Table 1). For most rearers, mealworm production was the main operation and source of income. In addition to rearing activities, the majority of the rearers also (partially) managed the reproduction process. Per tonne production, *total labour* requirements ranged between 0.02 and 0.14 FTE (Table 1) of which a maximum of 71% was classified as *own and family* labour. The majority – between 66% and 100% – of *total labour* was on the *direct care* of larvae. For reproduction, *direct care* activities included the weekly replacement of beetles, transferring eggs into small crates, and feeding the young larvae. Rearing activities entailed setting up crates with young larvae and feeding, harvesting, and sieving these larvae during the remainder of their life cycle. *Indirect care* activities, which accounted for a maximum of 34% of the required labour time, included administration, transport, marketing, and sales of mealworms.



*Table 3.1 Technical results of T. molitor farms in the Netherlands.*

| | Unit | Min | Max | n |
|---|---|---|---|---|
| **Production volume and labour** | | | | |
| Annual production volume | Tonne fresh larvae/year | 28.60 | 62.40 | 7 |
| Labour per farm | FTE[1] | 0.60 | 5.00 | 7 |
| Hired labour | FTE[1] | 0.65 | 4.50 | 7 |
| Own and family labour | FTE[1] | 0.00 | 3.00 | 7 |
| Labour per tonne | FTE[1]/tonne production | 0.02 | 0.14 | 7 |
| Direct care | % of total FTE[1] | 66 | 100 | 6 |
| Indirect care | % of total FTE[1] | 0 | 34 | 6 |
| **Feed input** | | | | |
| Dry feed | Tonne input/tonne production | 1.67 | 1.76 | 6 |
| Wet feed | Tonne input/tonne production | 1.70 | 3.59 | 6 |
| Feed conversion ratio[2] | | 1.72 | 1.96 | 6 |

[1] One FTE refers to one working week of 40 hours for 52 weeks in a year.
[2] Feed conversion was calculated as kilogram intake of dry matter per kilogram wet weight gain of fresh larvae, assuming that dry feed consists of approximately 90% and carrots of 11% dry matter.

The reproduction and rearing of mealworms took place, where possible, under controlled climate conditions (such as temperature and humidity) in designated breeding cells. The methods applied on the different farms were largely similar and most operations were carried out manually. The two-week reproduction phase included the laying of eggs and their hatching into small mealworms. The reproduction and rearing processes were continuous and most rearers applied a weekly set-up (placing the 14-day old larvae on the substrate in a breeding crate) and harvesting schedule. The majority of rearers followed a feeding schedule of dry feed once a week, and wet feed three times a week. Dry feed consisted of a grain-based mixture, and shredded carrots were mainly used as wet feed. The *feed conversion ratios*, i.e. the intake of dry matter per kilogram of wet weight gain of fresh larvae, ranged from 1.72 and 1.96 (Table 3.1). During harvest, the content of the crates was sieved to separate mealworms from the frass; there was no on-site processing at the time of the interviews. Alive fresh larvae were preferably transported on the day of harvesting as the maximum storage time of fresh larvae under cooled conditions is three days. Fresh larvae were destined for the petfood market and transported to customers in crates, preferably refrigerated. A few rearers were exploring the opportunities to sell their produce on the human food market.

***Economic results of T. molitor farms***

*Investments* differed between farms (Table 3.2). For *machinery and assets*, this variation was related to the purchase of new or second-hand material of varying quality. The main types of *machinery* used were carrot shredders, crate washing machines, sieves in various types and sizes to separate the mealworms from the frass, and forklifts. *Other assets* comprised climate control chambers, cooling systems, crates, and trolleys. *Non-allocated expenses* reported were those for *administration, marketing*, and *quality purposes*. The difference between the minimum and maximum value for these expenses was mainly caused by reporting differences.

The revenue streams originated from *sales of fresh larvae* and *frass*, as well as from the provision of *extension services* (Table 3.2). The large variation in *revenues* resulted from different *sales prices* for fresh larvae. Larvae were commonly sold in larger quantities for the petfood market. Rearers with longer rearing experience and presence in the sector had larger networks and appeared to have more bargaining power in sales price negotiations. *Revenues* from *frass* were not substantial, and some rearers did not receive any monetary compensation for frass which was partly due to the strict hygiene requirements for the (commercial) use of frass as fertiliser. The revenues for *extension services* are not specified in Table 3.2 for reasons of anonymisation, but are included in the *total revenues*.

*Table 3.2 Economic results of T. molitor farms in the Netherlands in EUR/tonne of fresh larvae production.*

| | Unit | Min | Max | n |
|---|---|---|---|---|
| **Investments** | | | | |
| Buildings and installations | EUR/tonne production | 2,159 | 6,817 | 3 |
| Machinery and other assets | EUR/tonne production | 841 | 4,747 | 6 |
| **Non-allocated expenses** | | | | |
| Administration, marketing, and quality | EUR/tonne production | 0 | 1,122 | 6 |
| Rent of buildings | EUR/tonne production | 58 | 769 | 4 |
| **Variable expenses** | | | | |
| Young larvae | EUR/tonne target produce | 1,000 | 1,980 | 6 |
| Dry feed | EUR/tonne production | 638 | 883 | 6 |
| Wet feed | EUR/tonne production | 108 | 437 | 6 |
| Hired labour | EUR/tonne production | 400 | 1,282 | 6 |
| Hired and own labour | EUR/tonne production | 677 | 2,913 | 6 |
| Utilities (energy, gas, water) | EUR/tonne production | 42 | 225 | 6 |
| Health (pest control and hygiene) | EUR/tonne production | 0 | 90 | 6 |
| **Revenues** | | | | |
| Sales of fresh larvae | EUR/tonne production | 3,100 | 4,278 | 7 |
| Frass | EUR/tonne production | 0 | 28.85 | 7 |
| Extension services | EUR/tonne production | n.a.[1] | n.a.[1] | n.a[1] |
| **Profitability** | | | | |
| GM without accounting for own labour | EUR/tonne production | 1,113 | 2,307 | 6 |
| GM after deducting "expenses" for own labour | EUR/tonne production | −180 | 2,030 | 6 |
| NPV without accounting for own labour | EUR/tonne production | −7,281 | 17,893 | 6 |
| NPV after deducting "expenses" for own labour | EUR/tonne production | −12,359 | 15,535 | 6 |

[1]n.a. = not applicable because of too few observations.

The main *variable expenses* included those for *labour*, *feed*, *utilities*, and *health* maintenance (Table 2). *Young larvae* (approximately 2 weeks old) were occasionally bought – e.g. when the volumes of young larvae from own reproduction were insufficient – at prices between 1.00 and 1.96 EUR/kilogram of fresh larvae target produce. Rearers indicated that at the time of the interview, it was more costly to buy young larvae externally than doing the reproduction in-house, yet it comes with a trade-off. On the one hand, the external purchase of young larvae entailed risks such as deviating larvae quality as well as the introduction of transmission of pests and diseases. On the other hand, the reproduction process is labour intensive, requiring advanced expertise. *Labour* and *feed* were the two largest variable expenses, also showing a high variation between farms. The large range (from 771 to 1,217 EUR/tonne production) for total expenses for *feed* resulted from differences in the amount of feed per tonne production (see Table 1) as well as varying availability and quality of wet feed. The large spread in *labour expenses* was related to the substantial difference between the amount of labour used per tonne production, from 0.02 to 0.14 FTE (Table 1). In addition, it was common for mealworm rearers to work with cheaper labour: employees with "a distance to the labour market", who have difficulties qualifying for a regular job, but are often good at performing routine work. Further *variable expenses* included those for *utilities*, in particular the electricity used for climate control and to a small extent gas use. The total water use was low as water was only used for cleaning the rearing crates and not recorded by farmers. Expenses for larvae *health* included pest control (moths) and maintenance of good hygiene in the facility. Expenses for disease prevention and treatment were not included in this category, as there were – according to participating rearers – no prevalent diseases for mealworms. *Total variable expenses* amounted to ranges between 1,693 and 2,444 EUR/tonne production and between 1,836 and 4,430 EUR/tonne production, with the first values not corrected and the second ones being corrected for unpaid (own and family) labour.

The NPV was negative before and after labour correction for three farms, and positive for two farms. For one farm the NPV turned into a negative value after labour correction. Farms with the lowest NPVs were characterised by both high investments and a relatively low GM due to lower sales prices of larvae. Those with a higher NPV mostly had relatively low investments and/or higher cashflows resulting from higher sales price of larvae and low variable expenses.

## 3.5 Discussion and conclusions

In the current study, we analysed profitability for small scale mealworm farms in the Netherlands with annual production volumes between 28.60 and 62.40 tonne fresh larvae. Production set-ups were largely similar and most rearers managed both the reproduction and rearing processes. Technical results showed large variations in labour requirements, wet feed input, and feed conversion rates. Economic results (initial investments, non-allocated and variable expenses) showed a large spread for nearly all elements of farm profitability. GM and NPV were calculated with and without accounting for own and family labour. In the latter situation, i.e. without accounting for the family hours spent, 3 out of 6 farms exhibited a positive NPV value. The large heterogeneity among farms was mainly related to the investment approach (new or second hand), fresh larvae sales prices, as well as feed and labour expenses. Comparing our GM range, i.e. from −180 to plus 2,030 EUR/tonne production of fresh larvae, with the feed and labour margins presented in Niyonsaba et al. (2021) of 7,620 to 13,770 EUR/tonne production, we find that these large differences are mainly rooted in the additional cost components we included in the gross margin and in different sales prices in the current study. Sales prices in the current study refer to farm-gate prices, whereas in Niyonsaba et al. (2021) these refer to market prices mostly in different European countries.

The negative NPV for four farms suggests that most insect farms are not profitable based on current investments, expenses, and revenues. A number of considerations should be taken into account when interpreting the NPV values. First, most farms rely on a relatively high share of own and family labour, which has been corrected for to allow for farm-to-farm comparisons. In reality, this labour is often unpaid, which may enable insect rearers to sustain production, even with low profitability. Second, farms with higher NPVs mostly had relatively low-cost investments. If such farms want to stay in the mealworm business, they probably have to invest in due term, while farms who already made more expensive investments (currently resulting in a lower NPV) are ready to scale up, likely leading to higher revenues and lower expenses. Third, the assumption of constant cash flows over the coming 20 years was based on a lack of information. In fact, market developments could lower future sales prices when production volumes increase, but prices could also rise as a result of increased demand. In addition, 2022 peaking feed and energy prices also illustrated that cash flows may actually differ over the years.



To increase the viability of mealworm farms, rearers would benefit from selling their larvae in niche markets in which they could potentially sell at higher prices. Rearers believed that sale prices are higher on the food market in particular. Enhancing consumer acceptance to insects and derivatives could aid to increase demand on the food market (Alhujaili et al., 2023). Additional revenue streams, such as offering extension services, could also increase the viability of the business model in the future. Revenues from frass may only substantially add to total revenues if its valuation for commercial sales increases. Insect frass is considered a promising alternative fertiliser, but the required sanitising treatment could eliminate its beneficial effect and therefore its commercial promotion and value (Poveda, 2021). To reduce variable expenses, feed and labour expenses require attention. Using side streams as a feed source could for instance provide opportunities for rearers to reduce feed expenses. However, the use of these streams as substrates poses challenges including constraints in European legislation, their applicability in terms of insects' dietary requirements, length of development cycle, variable quality, and their local availability (Ites et al., 2020; van Peer et al., 2021). Additionally, it is expected that with the move towards more circular agricultural activities, the demand for these waste streams will increase, as will their price (van Huis, 2022). Hall et al. (2021), Niyonsaba et al. (2021), and Yang and Cooke (2020) already recognised that insect farming based on manual activities is labour-intensive. Investing in mechanisation may reduce labour expenses, give opportunities to increase production volume, and decrease the cost price per unit due to economies of scale and scope (Hall et al., 2021; Rumpold and Schlüter, 2013). However, since market demand is still relatively low and unstable, high capital investments are perceived as a high financial risk (Niyonsaba et al., 2023).

The main limitation of this study is the small and heterogeneous sample. The emerging nature of the mealworm sector, and the lack of standardisation in terms of for instance production processes, quality, and end-products could explain the observed heterogeneity. The small and heterogeneous sample limits the informative value of the calculated ranges as a benchmark. Despite these constraints, our sample reflects the realities of the sector and can serve as an indicative benchmark. This was confirmed by rearers during and after the group discussion on preliminary results of this work. Furthermore, our sample included only small-scale farms (FTE < 5). As such, the results cannot be considered representative for the whole mealworm sector in the Netherlands (the sector comprises 25–30 mealworm farms), in which also a few larger scale insect farms operate. In addition, rearers currently do not separate expenses for reproduction and rearing processes, which prevents a comparison of external purchase and in-house reproduction. The inclusion of more and also larger farms would allow to make this separation and would provide valuable insights in the profitability potential of new business models, e.g. a decentralized model, in which reproduction and rearing are separated in specialized farms. Despite these limitations, our results provide the first important insights into mealworm and other insect farms' profitability. Extending the results to production of multiple insect types such as *H. illucens*, *A. domesticus*, and *L. migratoria* which follow different production systems and need different investments, will aid in the comparison of profitability between the different insect types.

The results of the current study aid in decision making for investors, credit providers, and other service companies, for instance as a benchmark in credit provision or insurance schemes design. The overview of technical and economic ranges provides these parties both insights in farm operations and estimates of the profitability of mealworm farms. The results further serve as a benchmark for mealworm rearers to guide them in making investment decisions or business model adjustments to increase profitability. Considering the high labour expenses, support through policy interventions could prioritise on subsidising mechanisation. Interventions should also focus on standardising for instance the insect rearing methods and quality of output. This will not only affect the uniformity of production processes, but also positively impact the consistency in quantity and quality of supply, which would further benefit actors downstream in the supply chain. Discussions with the participants revealed a strong need for chain coordination to increase the viability of mealworm farms, for instance when it comes to the facilitation of sales on the food market. Governmental agencies could play a role in promoting insects for food to stimulate the demand for insect-based products.

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**Supplementary material**

Supplementary material belonging to this chapter is available at:
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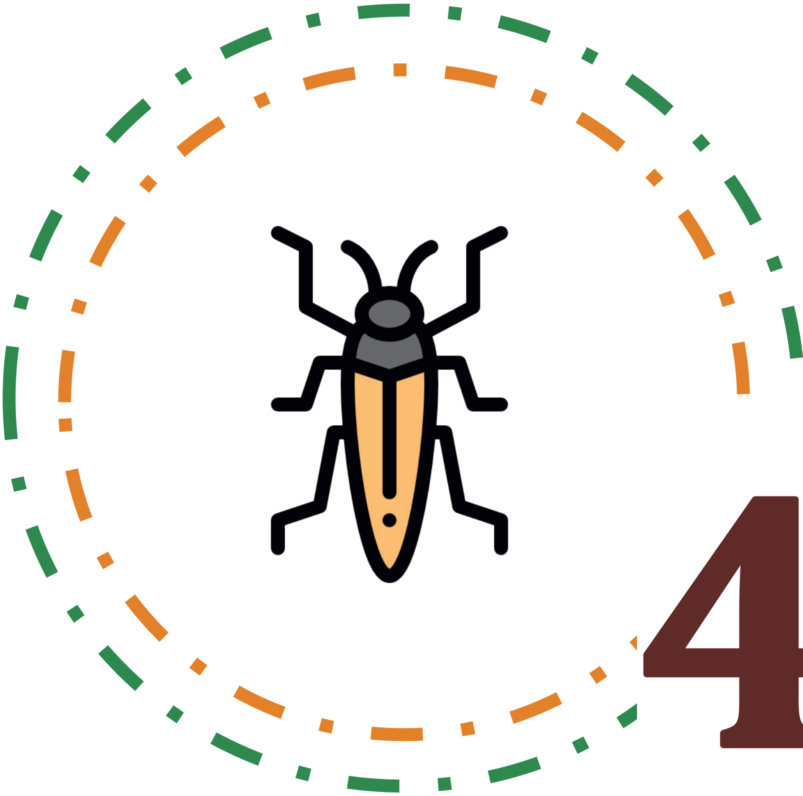

# 4

# Barriers, risks, and risk management strategies in European insect supply chains

This chapter is based on the paper: Niyonsaba, H.H., Höhler, J., Van der Fels-Klerx, H. J., Slijper, T., Alleweldt, F., Kara, S., Zanoli, R., Costa, A.I.A., Peters, M. Meuwissen, M.P.M., 2023. Barriers, risks, and risk management strategies in European insect supply chains. *Journal of Insects as Food and Feed*, 9(6), 691-705.
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**Abstract**

Despite technological developments and regulatory improvements, most actors in the insect sector still face many challenges and uncertainties. While previous research mainly focused on the perception of domain-specific challenges and risks or has been limited to specific stages in the supply chain, this chapter aims to determine how stakeholders perceive the importance of past barriers and future risks along European insect supply chains, and to identify the applied risk management strategies. Data were collected from stakeholders across four stages of the supply chain (rearers (n=23), processors (n=8), and insect-based feed (n=14), and food (n=12) producers) through an online survey. In total, 60 different barriers and risks, as well as 20 different risk management strategies, were evaluated. We find that stakeholders across all stages of the supply chain perceived "financial, cost, and market" barriers and risks as most important, specifically referring to the lack of financial investments and price and demand uncertainties. In addition, legal restrictions were perceived to constrain upscaling opportunities across all supply chain stages. Worker and food safety barriers were generally perceived as least important. The main risk management strategies across all stages of the supply chain related to investments in technologies enhancing stability of both the quality and the quantity of insects and derived products. Stakeholders were most optimistic about the future reduction of "operational" and "financial, cost, and market" risks. To further stimulate upscaling of the sector, we recommend enhancing financing opportunities, and to improve authorisations for the use of different substrates and the production of a wider set of insect-based ingredients for feed and food products.

**Keywords:** dynamic risk perception; stakeholder survey; risk attitude; insect sector; risk preference

## 4.1 Introduction

Large-scale insect production for feed and food purposes is gaining interest in Europe and many efforts have been made to improve both the technological and the regulatory landscape (IPIFF, 2019; Montanari et al., 2021a). The insect sector currently consists of many small- and medium-sized enterprises (SMEs) as well as some large companies (Derrien and Boccuni, 2018). Due to its young and dynamic nature, the European insect sector can be regarded as an emerging sector (Marberg et al., 2017) on the road to scaling up with investment interests on the rise (Montanari et al., 2021a; Rabobank, 2021). In 2020, the International Platform of Insects for Food and Feed (IPIFF), a European non-profit organisation, forecasted that its members will have invested more than 2.5 billion EUR by 2025 (IPIFF, 2020a). The exact number of current operators in Europe is not known, however, in 2022 IPIFF listed 80 members of which 53 were business operators in the insect sector, and the remainder academic institutions so-called observers (IPIFF, n.d.a).

European insect supply chains largely consist of four stages: rearers, processors, and insect-based feed and food producers. The first stage represents companies that rear insects from egg or larval to maturation phase; the second stage refers to companies processing fresh larvae into meal, oil, protein fraction, or other intermediate products; the third and fourth stages involve companies that incorporate the insect-based intermediate products in feed and food, respectively. In addition, insect-based products could be used in non-food and non-feed industrial applications such as cosmetic and textile-based products; however, this is not yet practiced commercially (Van Huis, 2022, Verheyen et al., 2020). Insect production and commercialisation for the feed market are more developed than for the food market, mainly because the EU legal framework provides more opportunities for insect-based feed than for insect-based food production (Montanari et al., 2021b). The production volume for feed may reach up to 2.7 million tonnes by 2030 (IPIFF, 2020a), which is ten-fold higher than the production volume for food. In the insect supply chain for food, the degree of vertical integration is low. A small number of companies focusses exclusively on the rearing of edible insects (IPIFF, 2020b; Montanari et al., 2021a; Pippinato et al., 2020). Most insect processors buy insects from rearers, process them, and sell the derived products (typically insect meal) as raw materials for food manufacturing. It is expected that the gradual opening of the European market will allow insect production for food consumption to expand to 260,000 tonnes by 2030 (IPIFF, 2020c). A rapid succession of authorisations took place since 2021, with full authorisation of the use of insect protein in poultry and swine feed and approval of four Novel Food applications, including “frozen” and “dried” *Locusta migratoria*; “dried”, “ground” and “frozen” *Acheta domesticus*; and “frozen”, “dried” and “ground” *Tenebrio molitor*. Novel Food applications allow for data protection and exclusivity, and therefore provide exclusive benefits to the applicant (IPIFF, n.d.b).

With both technical knowledge and regulatory landscapes evolving rapidly, European business opportunities are expanding. However, the majority of operators still faces considerable challenges in upscaling, limiting the emergence of a viable, large-scale European insect supply chain (Doberman et al., 2017, Van Huis et al., 2021). Insights into past barriers provide vital information on relevant remediation or prevention measures (Leonidou, 2004). A narrative evidence review conducted by Doberman et al. (2017) identified some of the hurdles hindering large-scale production and market adoption of insects as feed and food. The main barriers were a lack of knowledge on which species to rear, on optimal rearing conditions, and on the most favourable composition of substrates. Other reported hurdles were a low level of process automation and thus high labour costs. More recently, Yang and Cooke (2020) identified the following five primary challenges for upscaling production capacity of the edible insect industry in the United Kingdom: the need for (often expensive) high quality insect feeding substrates, slowly developing production techniques, challenging product development and marketing, lack of expertise on operational aspects of insect production, and regulatory uncertainties.

While we can measure the impact of past barriers, this is much more difficult to estimate for future risks (Komarek et al., 2020). The perception of occurrence and impact of future risks can inter alia influence the decision-making of operators and hence affect current and future business performance (Hardaker et al., 2015). Risk perceptions are domain-specific (Weber et al., 2002). Risks studied for the insect sector include food safety and potential microbiological risks (Vandeweyer et al., 2021), chemical risks (Meyer et al., 2021), allergenicity risks (Ribeiro et al., 2018), pest and disease risks (Van Huis, 2017), and technical and legal risks (Dobermann et al., 2017; Marberg et al., 2017). While domain-specific risk studies provide valuable insights, they do not rank the different risks across domains. Furthermore, their scope is typically limited to the barriers and risks posed to individual supply chain actors. To the best of our knowledge, this study is one of the first to study the perceived barriers and risks across multiple domains for European insect supply chains. Simultaneously studying multiple risks across domains is important as it helps producers to prioritise risks and implement appropriate risk management strategies (Komarek et al., 2020).

Enhanced knowledge of past barriers and future risks may improve financial and insurance services, and further enhance business performance and development (Bosma et al., 2018, Niyonsaba et al., 2021) as insights into how barriers and risks[8] change over time can help map the success of risk management. Risk management can be considered successful if the adopted strategies help reducing future risk perception compared to perceived past barrier, and contributes to the performance and value of enterprises in a

[8]In the context of this study, identical statements were assessed as both potential past barriers and potential future risks.

dynamic environment (Gordon et al., 2009; Hudáková and Masár, 2018; Mitra et al., 2015). In this regard, Dvorsky et al. (2021) recently highlighted the importance of risk identification and application of risk management strategies for smaller companies in young and dynamic sectors in general. Detailed and quantitative research on (the dynamics of) business risks and effective risk management strategies for emerging sectors is, nevertheless, rather scarce, mainly because of a lack of data (Mitra et al., 2015). This chapter contributes to a better understanding of effective risk management practices by providing insights into dynamic risk perceptions in the European insect sector.

This chapter first aims to identify the perceived importance of different barriers and risks, and to retrieve information on applied risk management strategies by stakeholders in European insect supply chains. Second, it aims to obtain insights into the dynamics of perceived barriers and risks over time.

## 4.2 Research methods

### *Survey design and data collection*

Four surveys[9] were designed with a similar set-up, modified for the four main insect supply chain stages of rearing, processing, and insect-derived feed and food producers. An overview of approaches used for the survey design, the data collection process and the main parts of the analysis is shown in Figure 4.1. Each survey covered four domains: (i) operations; (ii) finance, cost, and market; (iii) worker and food safety; and (iv) regulations. A literature-based longlist of different barriers for the commercialisation of insect proteins in Europe (Hartmann et al., 2017; Payne et al., 2016; Rumpold et al., 2013) was discussed with a group of researchers and representatives of industrial organisations involved in the European SUSINCHAIN[10] project to produce a final selected list of 60 unique barriers, further finetuned and divided into the four mentioned domains. As a result, 37, 24, 27, and 27 barriers were included in the surveys for rearers, processors, feed, and food producers, respectively. As the same barriers were also assessed as future risks, each statement was assessed for two time dimensions. In addition, a list of 20 risk management strategies was composed, based on, amongst others, Spiegel et al. (2021) and Slijper et al. (2020). In a separate meeting with seven experts from research and industry involved in the SUSINCHAIN project, strategies were adjusted to the insect sector. Finally, a set of five business specific statements was composed to assess risk attitude, based on similar statements used by Meraner and Finger (2019), Meuwissen et al. (2001), and Slijper et al. (2020).

[9]Surveys can be found in the Supplementary material (S.1.1–S.1.4).
[10]These member organisations were taking part in the SUSINCHAIN project (https://susinchain.eu/).

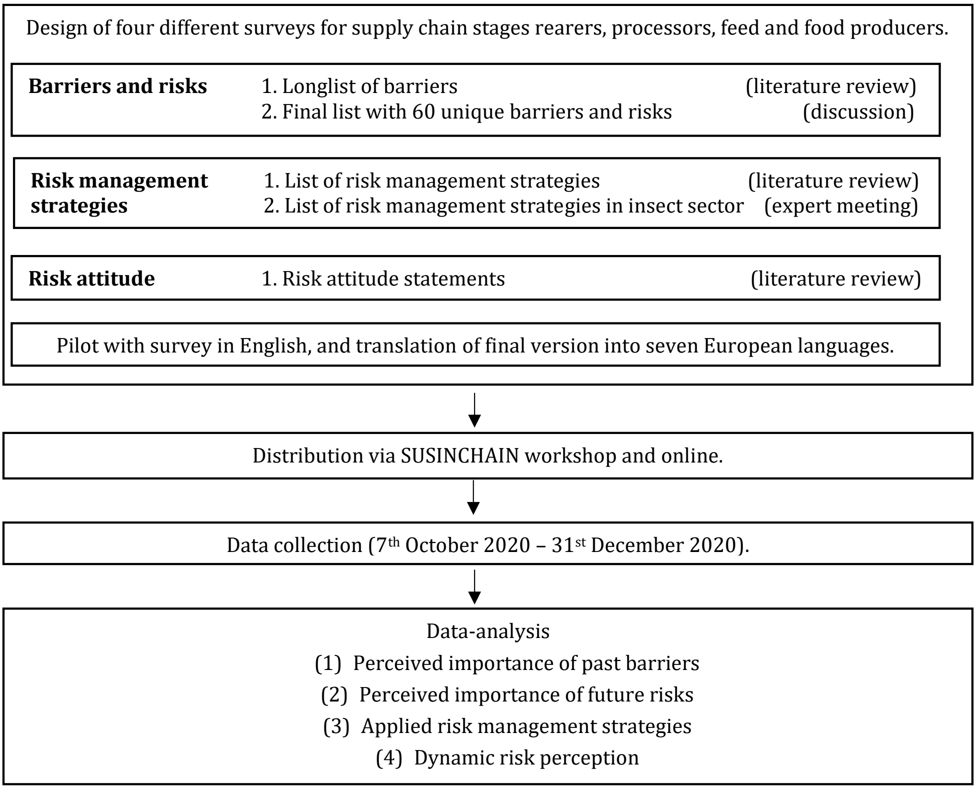


*Figure 4.1 Overview of survey design, data collection, and main parts of the analysis.*

The first part of the survey collected general information about the stakeholder (demographics) and company, including the produced insect species, number of full-time employees, and production volume. The second part assessed the perceived importance of past barriers and future risks. Respondents were asked to score both the occurrence frequency and the negative impact of each barrier in the past five years on a 5-point Likert scale ranging from 1 (never/no negative impact at all) to 5 (always/very severe negative impact). The same scales were used to score future risk (five years). A Likert scale assessment is often used to measure latent variables using several items. The combination of these items enables researchers to better measure latent variables. Previous studies investigating risk perception also used Likert scales, see e.g. Rahman et al. (2021), Rizwan et al. (2020), and Wauters et al. (2014). Respondents were asked to explain their scores and to point out the most important past barrier and future risk for each domain. Furthermore, respondents were requested to explain how they managed the perceived most important past barrier and which strategy they planned to use to manage the most important future risk. The third part of the survey inquired about past and current risk management strategies. At this point, respondents were also given the opportunity to include risk management strategies that were not provided in the questionnaire.

Additionally, this third part of the survey assessed respondents' relative risk attitude by asking about their level of agreement on five statements on a 5-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). These five statements were framed as follows: I am more willing to take more risks on the aspects of (1) production, (2) marketing, (3) financial matters, (4) management in general, and (5) scaling-up of the business compared to colleagues. Parts 2 and 3 of the survey elicited latent variables, which are variables that cannot be measured using a single item. Latent variables can be measured in formative or reflective way. In contrast with reflective indicators, formative measures imply that changes in items will cause changes in latent variables (Diamantopoulos et al., 2006; Coltman et al., 2008). All latent variables, i.e. risk perception, the combinations of adopted risk management strategies, and risk attitudes, were measured in a formative way. This makes checks for internal consistency reliability redundant (Diamantopoulos et al., 2006).

Surveys were designed in English and then piloted by two Dutch insect operators (one insect rearer and one food processor) and one industry representative. After this pilot, the English surveys were translated into seven European languages: Danish, Dutch, French, German, Italian, Portuguese, and Spanish, and reviewed by native speakers with experience in the insect sector. The survey was administered online via Qualtrics (Qualtrics, Provo, UT). The survey was distributed to businesses operating in or organisations connected to the insect sector. Respondents from sector organisations were asked to represent 'average' member companies; researchers and consultancies were requested to base their answers on their expertise. Initial distribution occurred during a workshop facilitated by the SUSINCHAIN project, followed by further dissemination via social media, conferences, and industry organisations. Via a general invitation respondents could choose the survey version for the supply chain stage they felt most connected to. In case a respondent was not familiar with a question or topic of the survey, the particular survey questions(s) could be left unanswered. Responses were collected between 7th of October and 31st of December 2020. During this period, there were no insect related crises or policy changes affecting the insect sector.

***Sample characteristics***

Table 4.1 displays the total number of respondents as well as the number of completed and included (at least 50% of the questions related to past barriers and future risks) survey responses per supply chain stage. Three respondents answered the survey for more than one supply chain stage. Response rates could not be calculated as the survey was distributed online and no specific number of respondents was targeted. Convenience sampling is considered sufficient to answer our research questions since due to the small and emerging nature of the insect sector, the pool of potential respondents is rather limited.

A minority of respondents elaborated on their barrier and risks scorings. On average, 65% (rearers: 71%; processors: 70%; feed producers: 60%; food producers: 59%) of the respondents mentioned strategies to overcome the indicated most important barrier or risk. On average, 89% (rearers: 91%; processors: 88%; feed producers: 93%; food producers: 83%) of the respondents indicated which risk management strategies were applied in the respective supply chain stages, and 13 additional risk management strategies were mentioned.

*Table 4.1 Number of respondents per supply chain stage.*

| Supply chain stage | *n* total responses[1] | *n* completed surveys[2] | *n* included responses[3,4] |
|---|---|---|---|
| **Rearers** | 84 | 25 | 23 |
| **Processors** | 41 | 10 | 8 |
| **Feed producers** | 81 | 16 | 14 |
| **Food producers** | 43 | 15 | 12 |

[1]Respondents who started the survey.
[2]Respondents who finished the survey without necessarily answering every question.
[3]Respondents who finished the survey and answered more than 50% of barrier and risk questions; this group is considered for further analysis.
[4]Three respondents (within included responses) answered the survey for more than one supply chain stage.

Respondents for the supply chain stages rearers, processors, feed, and food producers originated from 12, 6, 6, and 7 different countries, respectively[11]. Included survey responses originated from 11 different European and four non-European countries; the most represented countries were: the Netherlands (n=11), Belgium (n=10), Germany (n=7), and Italy (n=6). On average, 58% of responses came from companies (rearers: 74%; processors: 62%; feed producers: 43%; food producers: 54%), others were from business associations (8.5%), research organisations (16%), or other organisations (17.5%) such as technology suppliers and consultancies. Although researchers are generally not regarded as sector stakeholders, their responses were included as they were considered to have a good understanding of the risks for specific supply chain stages. The size of the companies, in terms of the average FTEs (full time equivalent, 1 FTE = 40 hours per week), was relatively small, except for companies associated to feed production. The dominance of low FTE organisations among survey respondents reflects the dominance of SME and young insect businesses in the European insect sector. The size of research institutes was left out from the analysis. The main insect species reared, processed, or researched included: *H. illucens* (black soldier fly), *T. molitor* (yellow mealworm), and – though to a lesser extent – *A. domesticus* (house cricket) and *A.* diaperinus (lesser mealworm).

[11]An overview of the number of respondents per supply chain stage per country can be found in the online Supplementary material (S.3.1).

***Analysis***

Survey responses were analysed using IBM SPSS Statistics for Windows (25$^{th}$ version). Analyses were performed following the steps specified for each objective below.

*Objective 1:* *to identify the perceived importance of different barriers and risks, and to retrieve information on applied risk management strategies by stakeholders in European insect supply chains.*

For each past barrier and future risk, a score (Eq. 4.1 and 4.2) was computed – per respondent – from the respective frequency and impact score:

*Past barrier score = frequency of barrier in the past* x *negative impact of barrier in the past* (4.1)

*Future risk score = frequency of risk in the future* x *negative impact of risk in the future* (4.2)

Subsequently, from all respondent scores, the averages and standard deviations were computed for each barrier and risk. These averages thus reflect the perceived importance, averaged over individuals per supply chain stage, for each separate barrier or risk. They were used to rank the five most important barriers and risks perceived by stakeholders for each of the four supply chain stages. Answers to open-ended questions related to strategies to overcome the most important barriers and risks (specified per domain) were used to gain insights into such strategies applied by operators.

*Objective 2:* *to obtain insights into the temporal dynamics of perceived barriers and risks of stakeholders.*

The dynamic risk perception was defined as the difference between the future risk score and the past barrier score, for each individual respondent (Eq. 4.3):

*Dynamic risk perception score = future risk score – past barrier score* (4.3)

Paired sample *t*-tests were run to test for statistically significant differences ($\alpha = 0.05$) between future risk and past barrier scores. Regarding data validity used for these paired sample t-tests, we made the following assumptions: (1) the observations (between subjects) are independent, and (2) each paired measurement is taken from the same subject. In addition, the average dynamic risk perception score across all risk domains was computed for each respondent. This average dynamic risk perception score reflects the average difference between future risk scores and past barrier scores for one respondent. Based on this average score, respondents were categorised into one of the following groups: one with a negative average dynamic risk perception (i.e. future risks were perceived to be smaller than past barriers) or one with a positive average dynamic risk perception (i.e. future risks were perceived to be larger than past barriers). These respondent groups were then profiled using descriptive statistics including their applied risk management strategies and risk attitude.

## 4.3 Results

Table 4.2.A and 4.2.B show perceived importance of past barriers and future risks. Per supply chain stage, the five most important barriers and risks are highlighted. The complete results can be found in the Supplementary material (S.2.1 and S.2.2).

***Perceived importance of past barriers***

Stakeholders in all stages perceived barriers from the “finance, cost, and market” domain as most constraining (Table 4.2.A and 4.2.B), followed by barriers from the “regulations” and “operations” domains. Barriers from the “worker and food safety” domain were generally not seen as a major impediment to business performance. For most supply chain stages, top-five barriers comprised different domains, except for the processors’ stage, for which all top-five barriers originated from the “finance, cost, and market” domain.

Regarding barriers in the “operations” domain, the *lack of mass rearing techniques* (14.2) has most severely affected rearers. Hence, feed producers underscored the *insufficient scale of production of insects or insect-based ingredients for commercial use as ingredients in feed* (9.5) for feed producers. For food producers the *limited knowledge on the use of insects as ingredients* (15.9) was regarded as most constraining.

Within the “financial, cost, and market” domain, the most constraining barriers related to the high operational costs of insect production and further processing. These costs included *high labour costs* for rearers (13.5) and processors (14.4), as well as *high unexpected costs* (10.7) and *high prices of insects and insect-based ingredients for further processing* (12.8) for feed producers. In addition, the *lack of possibilities to sell insect frass* (12.6) has limited the business performance of rearers. Furthermore, *the limited access to finance* has affected processors (16.3) and feed producers (10.0), while processors were also constrained by the *unavailability of subsidies for investments* (17.6). Regarding the market for insects and insect-based products, the *lack of social acceptance of production and products* was perceived as most constraining for processors (15.5) and food producers (15.5). Accordingly, the *volatile market demand for produce* (17.9) and *insufficient market demand for insect-based products* (19.3) were considered as important barriers for the business performance of processors and food producers, respectively.

Within the “regulations” domain, barriers including the *legal restrictions on the use of waste and by-products as rearing substrates* (12.7) and *legal restrictions preventing the use of processing-waste or frass* (12.6) were considered as most limiting. More downstream the supply the chain, feed and food producers were affected by restrictions regarding product development. For feed producers this included *legal restrictions concerning the use of insect meal in feed* (11.5), and for food producers *national legal restrictions concerning the use of insects in food* and *lack of safety data for submission of legal registration* (17.4).

*Table 4.2.A Average barrier (B) and risk (R) scores for rearers, processors, feed and food producers. Top-five scores per supply chain stage are in bold. Empty cells indicate that this barrier or risk was not included for this stage. Barriers and risks presented in this table are shortened versions; full phrases are presented in the Supplementary material (S.2.1). S.2.2 displays averages of perceived frequency, impact, and multiplied score (frequency x impact) of barriers and risks.*

| **Description** | **Rearer (n=23)** | | **Processor (n=8)** | | **Feed producer (n=14)** | | **Food producer (n=12)** | |
|---|---|---|---|---|---|---|---|---|
| | B | R | B | R | B | R | B | R |
| **OPERATIONAL BARRIERS AND RISKS** | | | | | | | | |
| Lack of information on best species for mass rearing | 7.9 | 4.9 | | | | | | |
| Lack of information on optimal rearing conditions | 11.6 | 7.7 | | | | | | |
| Unstable supply of eggs or larvae for rearing | 8.8 | 8.4 | | | | | | |
| Unstable quality of substrate(s) supply for rearing | 9.1 | 7.7 | | | | | | |
| Unstable quantity of substrate(s) supply for rearing | 6.2 | 7.7 | | | | | | |
| Lack of quality standards and best practice guidelines | 8.1 | 9.1 | 9.3 | 8.3 | | | | |
| Lack of mass rearing or processing techniques | **14.2** | **11.9** | 11.2 | 8.1 | | | | |
| Insect diseases which infect insect colonies | 7.6 | 9.7 | | | | | | |
| Pest insects and insect diseases which infect colonies | 9.9 | 8.8 | | | | | | |
| Presence of rodents in the insect rearing facility | 3.3 | 3.1 | | | | | | |
| Lower production volumes due to extreme weather | 6.2 | 4.6 | | | | | | |
| Lack of data on the effect of insect processing techniques on nutritional content | | | 11.4 | 8.4 | | | | |
| Lack of validated safe methods and guidance for storage, packaging and transport of eggs and larvae | | | 9.8 | 9.4 | | | | |
| Insufficient scale of production of insects for commercial use as ingredients in feed or food | | | | | **9.5** | **11.5** | 11.0 | 8.4 |
| Lack of consistency in quality of incoming insects | | | | | 5.2 | **9.1** | 10.4 | 8.2 |
| The need to source insects with difference in quality | | | | | 4.5 | 6.6 | 10.5 | 8.0 |
| Limited validation of using specific insect species in diets for livestock under practical conditions | | | | | 5.2 | 7.4 | | |
| Limited availability of data on sensory perception of consumers regarding insect-based food | | | | | 4.1 | 6.4 | 10.1 | 9.4 |
| Limited knowledge the use of insects as ingredients | | | | | 7.8 | 6.1 | **15.9** | 9.4 |
| Lack of best practice guidelines for insect-based food production | | | | | | | 12.8 | 9.17 |
| **FINANCIAL, COST, AND MARKET BARRIERS AND RISKS** | | | | | | | | |
| Unavailability of subsidies for investment | 11.4 | 9.4 | **17.6** | 9.7 | 9.3 | 6.7 | 14.7 | 10.4 |
| Limited access to finance | 11.1 | 10.9 | **16.3** | **11.3** | **10.0** | 5.8 | 14.9 | 10.3 |
| Unavailability of business insurance for companies | 5.2 | 7.3 | 6.4 | 6.7 | 2.4 | 3.8 | 7.9 | 7.0 |
| Technological innovations which decrease current asset values | 7.7 | 8.3 | 9.5 | 8.9 | 6.5 | 5.1 | 7.8 | 7.7 |
| High labour costs | **13.5** | **11.9** | **14.4** | 10.1 | | | | |
| High prices of young larvae for rearing or insect-based ingredients for further processing | 5.3 | 4.7 | 10.5 | 8.7 | **12.8** | **9.3** | 13.8 | 8.8 |
| High prices of substrate(s) for rearing | 7.2 | 9.0 | | | | | | |
| Price fluctuations of young larvae for rearing or insect-based ingredients for further processing | 5.0 | 5.0 | 9.1 | 9.7 | 7.8 | 8.3 | 7.9 | 6.8 |
| Price fluctuations of substrate(s) for rearing | 5.5 | 8.1 | | | | | | |
| Low market prices of insects or derived products | 9.7 | **12.9** | 9.5 | 9.1 | 9.2 | **10.4** | 8.3 | 7.1 |
| Price fluctuations of insects or insect-based products | 8.1 | 11.6 | 6.8 | **10.9** | 6.1 | 7.9 | 7.8 | 7.7 |
| Lack of possibilities to sell insect frass | **12.6** | 9.6 | 10.4 | 9.4 | | | | |
| Volatile market demand for produce | 12.0 | 9.7 | **17.9** | **12.9** | | | | |
| Lack of social acceptance of production and products | 11.1 | 8.3 | **15.5** | **13.5** | 5.4 | 5.2 | **15.5** | **15.3** |
| Late payment from buyers | 5.5 | 6.1 | 7.0 | 7.0 | 3.3 | 3.2 | 6.3 | 5.5 |
| Seasonal downturns in revenue | 6.3 | 5.1 | | | 6.3 | 5.0 | 8.8 | 5.4 |
| High unexpected costs | 9.8 | 7.5 | 12.6 | 10.6 | **10.7** | 7.5 | 10.7 | 7.6 |
| Insufficient market demand for insect-based products | | | | | 7.0 | 6.8 | **19.3** | **14.1** |

*Table 4.2.B Average barrier (B) and risk (R) scores for rearers, processors, feed, and food producers. Top-five scores per supply chain stage are in bold. Empty cells indicate that this barrier or risk was not included for this stage. Barriers and risks presented in this table are shortened versions; full phrases are presented in the Supplementary material (S.2.1). S.2.2 displays averages of perceived frequency, impact, and multiplied score (frequency x impact) of barriers and risks.*

| **Description** | **Rearer (n=23)** | | **Processor (n=8)** | | **Feed producer (n=14)** | | **Food producer (n=12)** | |
|---|---|---|---|---|---|---|---|---|
| | B | R | B | R | B | R | B | R |
| **WORKER AND FOOD SAFETY BARRIERS AND RISKS** | | | | | | | | |
| Allergenicity potential for workers caused by insects or related products | 8.7 | 7.1 | 8.3 | 8.7 | 3.9 | 6.2 | 5.1 | 5.6 |
| Other health problems for workers due to working with insects | 5.3 | 5.3 | | | | | | |
| Microbiological hazards in insects related to substrate use | 6.2 | 6.5 | | | | | | |
| Chemical hazards in insects related to substrate use | 4.5 | 6.0 | | | | | | |
| Lack of knowledge on the safety of insect production or insect-based products | 9.1 | 6.4 | | | 7.6 | 6.7 | 7.6 | 5.8 |
| Microbiological risks related to storage, packaging, and transport | | | 9.0 | 8.4 | | | | |
| Lack of data on the impact of processing techniques on food safety of products | | | 12.3 | 8.0 | | | | |
| Lack of traceability systems in place for insect transport and logistics | | | 7.7 | 6.6 | | | | |
| Allergenicity potential of insect-based feed for animals | | | | | 1.9 | 3.6 | | |
| Lack of data on the impact of insect-based feed on animal performance and health | | | | | 6.9 | 7.2 | | |
| Allergenicity potential for consumers from insect-based food products | | | | | | | 7.3 | 6.4 |
| Uncertainty regarding the impact of insect-based food products on human health | | | | | | | 6.2 | 7.3 |
| **REGULATORY BARRIERS AND RISKS** | | | | | | | | |
| Legal restrictions on the use of waste and by-products as rearing substrates | **12.7** | **13.6** | | | | | | |
| Legal restrictions preventing the use of processing-waste or frass | **12.6** | **13.6** | 8.9 | 10.6 | | | | |
| Difficulties to obtain operating licenses for the company | 11.4 | 8.8 | 8.9 | **12.0** | | | | |
| Regulations regarding environmental emissions | 7.3 | 7.2 | | | | | | |
| Lack of safety data for submission of legal registration | | | | | 8.1 | 8.7 | **17.4** | **11.5** |
| Legal restrictions concerning the use of insect meal in feed | | | | | **11.5** | **10.5** | | |
| Other legal restrictions (e.g. labelling requirements insect-based feed and food) | | | | | 5.7 | 6.3 | 6.3 | 6.3 |
| Other legal restrictions (e.g. labelling requirements for food from animals fed with insects) | | | | | 5.3 | 8.2 | | |
| Administrative and financial burden for the authorisation of insects as food at EU level | | | | | | | 13.6 | **11.8** |
| National legal restrictions concerning the use of insects in food | | | | | | | **19.2** | **13.9** |

### *Perceived importance of future risks*

"Finance, cost, and market" risks were expected to be most constraining for the future, followed by "regulatory" and "operational" risks (Table 4.2.A and 4.2.B). On the contrary, risks related to "worker and food safety" were not considered to be among the top-five risks across supply chain stages.

With regard to "operations", rearers expected that the *lack of mass rearing or processing techniques* (11.9) will be most constraining in the future, which was expected by feed producers to result in an *insufficient scale of production of insects for commercial use as ingredients in feed* (11.5). Feed producers also considered the *lack of consistency in quality of insects* (9.1) as an important risk for the future.

"Financial, cost, and market" risks across chain stages mainly comprehended price and demand risks, and – to a lesser extent – risks related to high operational costs. These high operational costs included *high labour costs* (11.9) for rearers and *high prices of insects or insect-based ingredients for further processing* (9.3) for feed producers. In addition, processors feared a *limited access to finance* (11.3) which would affect future business performance. Regarding price risks, the *low market prices of insects or derived products* were perceived as constraining for rearers (12.9) and feed producers (10.4). For processors, the *price fluctuations of insects or insect-based products* (10.9) were regarded as an important risk. With respect to the market for insects and insect-based products, both processors and food producers considered the *lack of social acceptance of production and products* (resp. 13.6 and 15.3) as an important factor affecting future business performance. This perception was also illustrated by the estimated impact of the *volatile market demand for produce* (12.9) for processors and the *insufficient market demand for insect-based products* (14.1) for food producers.



With respect to "regulatory" risks, stakeholders expected a negative impact from constraints on various aspects for the different supply chain stages. For rearers, the *legal restrictions on the use of waste and by-products as rearing substrates* (13.6) and *legal restrictions preventing the use of processing-waste or frass* (13.6) were projected to remain most constraining in the future. Similar constraints included *difficulties to obtain an operating license for the company* (12.0) for processors and *legal restrictions concerning the use of insect meal in feed* (10.5) for feed producers. For food producers, it concerned *national legal restrictions concerning the use of insects in food* (13.9), as well as *lack of safety data for submission of legal registration* (11.5) and related *administrative and financial burden for the authorisation of insects as food at EU level* (11.8).

***Applied risk management strategies***

Across supply chain stages, *investing in technologies for production and safety thereof* was among the most frequently applied strategies in the domains of "operations" and "worker and food safety" (Table 4.3). With respect to "operational" strategies, *investing in technologies for consistent quality of production* along with *investing in technologies for consistent quantity of production* were among the top-five strategies applied in most supply chain stages. In addition, rearers and feed producers relied on diversification strategies in production. “Financial, cost, and market” strategies applied by processors and food producers included *ensuring access to loans or external funds* and *minimising debts to keep financial risks low*. Furthermore, *using contracts* to guarantee consistency in quantity or quality was frequently applied by feed producers. Regarding “worker and food safety” strategies, *investing in technologies for hygiene control* was among the top-five strategies applied in all supply chain stages. “Other” strategies, such as *being a member of cooperatives or business associations* were not very popular risk management strategies for operators, except for processors for whom the strategy *being a member of a cooperative* was among the top-five.

Answers to the open question on stakeholders’ perception of the capacity among business operators to overcome barriers and risks revealed a large heterogeneity across individual respondents and domains. In this regard, stakeholders were especially positive about overcoming “operational” risks, in contrast to “regulatory” risks. Stakeholders indicated for instance that operators felt quite able to overcome the barrier of *lack of technologies*, *small-scale production* and *high labour costs*. Main strategies used in this respect included *doing research*, *experiments,* and *developments of automated systems, both in-house and in collaboration with other start-ups.* Regarding strategies for “financial, cost, and market” risks, *cooperating with other businesses* along with *doing market research* were frequently applied in the sector to improve and enlarge the market for insects. Furthermore, stakeholders observed the desire *to set up long-term relationships* and *make use of contracts* to keep price and demand risks as low as possible. With regard to improvement of the social acceptance of insect products, the main applied strategy across stages included *educating consumers*. With respect to “regulatory” risk strategies, the most important strategy was to *provide more clarity about production and processing* and *to invest time and efforts into lobbying with the authorities.* In addition, stakeholders indicated that *cooperating with other businesses or stakeholders* was more frequently applied to overcome “regulatory” risks compared to other types of risks.

*Table 4.3 Applied risk management strategies in supply chain stages: rearers, processors, feed, and food producers. Top-five strategies per stage are in bold. Numbers reflect percentage of respondents who apply the strategy. Empty cells indicate that this risk management strategy was not included for this supply chain stage. Risk management strategies presented in this table are shortened versions. Full phrases are presented in the Supplementary material (S.2.3).*

| **Description** | **Rearer (n=23) (%)** | **Processor (n=8) (%)** | **Feed producer (n=14) (%)** | **Food producer (n=12) (%)** |
|---|---|---|---|---|
| **OPERATIONAL STRATEGIES** | | | | |
| Investing in technologies for consistent quality of production | **87** | **50** | **57** | **42** |
| Diversifying business activities | 22 | 38 | **50** | 33 |
| Diversifying insect species for production | 17 | 25 | 21 | 33 |
| Producing for feed and food purposes or using different product applications | **52** | 25 | **50** | 17 |
| Having an all-in-all-out system | 30 | 13 | 7 | 17 |
| Having multiple production or processing lines | 22 | 25 | 21 | 17 |
| Using market information to plan business activities for the next season | 35 | | | |
| Investing in technologies for consistent quantity of production | **78** | **63** | 43 | **42** |
| **FINANCIAL, COST, AND MARKET STRATEGIES** | | | | |
| Ensuring access to loans or external funds | 43 | **63** | 36 | **58** |
| Keeping financial reserves for possible financial downtimes in the future | 39 | 38 | 43 | 33 |
| Minimising debts to keep financial risks low | 13 | 25 | 29 | **58** |
| Having an additional job outside the insect business | 13 | 25 | 21 | 25 |
| Buying insurance | 26 | 38 | 0 | 25 |
| Using contracts | 13 | 25 | **50** | 17 |
| Improving labour flexibility | 17 | 25 | 29 | 33 |
| Purchasing inputs or selling outputs jointly with other rearers or processors | 0 | | | 25 |
| **WORKER AND FOOD SAFETY STRATEGIES** | | | | |
| Investing in technologies to control environmental risks | **57** | 38 | 21 | 33 |
| Investing in technologies for hygiene control | **57** | **50** | **57** | **58** |
| **OTHER STRATEGIES** | | | | |
| Being a member of a cooperative | 17 | **63** | 0 | 8 |
| Being a member of a business association | 35 | 13 | 43 | 33 |

### *Dynamic risk perception*

Looking at multiple risk domains simultaneously, the perceived risks were considered smaller in the future as compared to the past for processors and food producers, which can be seen from the significantly negative dynamic risk perception scores of –1.39 *(p=0.001)* and –1.90 *(p=0.000)*, respectively, in Table 4.4 (bottom row). This result is in line with those listed in Table 4.2, indicating sometimes large differences between barrier and risk perception. Stakeholders expected risks to reduce in the future, especially in the case of "operational" and "financial, cost, and market" risks, with a score of 0.74 *(p=0.001)* and 0.76 *(p=0.020)* (final column), respectively. Again, this is in line with results presented in Table 4.2, showing a decline in risk perception. In addition, it is noteworthy that for all supply chain stages except for food producers, "regulatory" risks were expected to increase in the future, an observation that could be related to the difficulties stakeholders foresaw in overcoming this type of risk. We realise that the small sample size for the supply chain stage processors is not representative to provide conclusive evidence on the dynamic risk perception for this chain stage. We believe, however, that our results do provide suggestive evidence. Comparing the individual dynamic risk perception between operators, 31 of 55 stakeholders perceived future risks on average to be smaller compared to the past. With regard to risk management, operators with a predominantly positive dynamic risk perception applied fewer strategies, but risk attitude was nearly equal between the groups. Details on profiles for the two groups are shown in the Supplementary material (S.2.5).

*Table 4.4 Dynamic risk perception scores per supply chain stage and per risk domain. P-values of paired sample t-tests are between brackets. Significant differences (p < 0.05) are in bold.*

| | **Rearers (n=23)** | **Processors (n=8)** | **Feed producers (n=14)** | **Food producers (n=12)** | **All supply chain stages** |
|---|---|---|---|---|---|
| Operations | **−0.91** ***(0.035)*** | −1.88 *(0.059)* | **1.46** ***(0.021)*** | **−2.53** ***(0.014)*** | **−0.76** ***(0.020)*** |
| Finance, cost, and market | 0.14 *(0.693)* | **−1.78** ***(0.003)*** | **−1.15** ***(0.007)*** | **−1.59** ***(0.001)*** | **−0.74** ***(0.001)*** |
| Worker and food safety | −0.28 *(0.604)* | −1.39 *(0.093)* | 0.60 *(0.188)* | −0.38 *(0.665)* | −0.23 *(0.477)* |
| Regulations | 0.23 *(0.777)* | 2.43 *(0.090)* | 0.84 *(0.144)* | **−3.25** ***(0.009)*** | −0.27 *(0.596)* |
| All risk domains | −0.25 *(0.295)* | **−1.39** ***(0.001)*** | 0.04 *(0.874)* | **−1.90** ***(0.000)*** | |

## 4.4 Discussion

***Comparison to previous research and other sectors***

Since research on barriers and risks for the insect sector is rather limited, we do not only compare our findings with observations from previous studies in the same sector but also with those from other emerging sectors. In addition, we interpret our results in the context of barriers and risks which are typically experienced by small companies.

An important "operational" barrier for rearers was the lack of automation techniques for large scale production, which inter alia leads to insufficient quantities of insects and insect-based ingredients for further processing as perceived by feed producers. These results confirm previous findings for the insect and other sectors. Rumpold et al. (2013) already emphasised the need for automated and cost-effective production processes in the insect industry. In addition, Sogari et al. (2019) suggested in their review that automation techniques will help to increase production scale and reduce labour intensity allowing for stable product quality and competitive product pricing. Comparable observations were made for the algae sector, where the costs of raw materials, the required labour, and the small-scale operations resulted in high production costs (Fernández et al., 2021). High operational costs also affected the mussel sector (Gren et al., 2021). Concerning other "operational" matters, Van Huis et al. (2021) highlighted potential pathogen infection as a major concern for insect rearing. In our study, this risk was considered of medium concern relative to other "operational" barriers.

"Financial, cost, and market" barriers and risks were consistently ranked as most important among all domains and across chain stages. The volatile and insufficient market demand, due to factors such as high sales prices of insects and insect-based feed products as well as limited social acceptance of food products, were main concerns. The low social acceptance of insect-based food products has been thoroughly discussed before by, for instance, Onwezen et al. (2021), who concluded that insects have the lowest consumer acceptance among various alternative protein sources. Intensive consumer education and new product development efforts are required to reach higher consumer acceptance (Naranjo-Guevara et al., 2021; Ngo et al., 2021). The observed importance of "financial, cost, and market" risks as perceived by stakeholders correspond to those commonly experienced by smaller companies (Ali et al., 2017; Yang, 2017) and in other emerging sectors (Ahsan et al., 2010). Ahsan et al. (2010), for instance, obtained similar findings for the mussel industry where market risks regarding future demand and volatile prices were perceived as important by stakeholders. The difficulty for small companies to obtain financing has also been described before. Enzing et al. (2014), for instance, identified access to finance as one of the main non-technological barriers for companies operating in the algae sector. The difficulty to obtain financing is often related to information asymmetry between small companies and finance providers on firm performance and financial statements (Moro et al., 2015). For companies operating in emerging sectors, information provision and symmetry become even more relevant as they operate in a fast-changing business environment, often characterised by a high level of uncertainty, with changing regulations and market conditions.



In our study, "worker and food safety" barriers and risks were consistently regarded as least important. This result contrasts with findings by Skotnicka et al. (2021), who mentioned the relevance of food safety concerns for consumers and their role in the social acceptance of insect-based products. The difference could be explained by their focus on consumers versus our focus on supply chain operators. Apparently, insect operators feel they can handle safety problems for workers and their products quite well.

"Regulatory" barriers and risks were perceived as highly relevant for all chain stages. Dobermann et al. (2017) and Yang and Cooke (2020) obtained similar findings, as did Araújo et al. (2021), Rumin et al. (2021), and Ahsan et al. (2010) for other emerging sectors; the former two studies in the context of the algae and the latter one of the mussel sector. These emerging sectors face(d) comparable regulatory barriers, specifically in relation to changing regulations and the high complexity of administrative procedures and licensing. The large impact of regulatory constraints for SMEs in young and innovative sectors has been described before as a barrier for business model innovation to enhance firm performance (Ulvenblad et al., 2018). In the context of the current study on European insect supply chains it is, however, important to note that European regulations have further progressed since the time of data collection. Although the implemented changes were foreseeable when the survey was conducted, respondents still regarded "regulatory" risks as highly relevant and as limiting factors for many different aspects of production. European regulations pertaining to the use of different substrates did not change so far. The approval of cheaper substrates and the permission to sell insect by-products could benefit the profitability of rearing companies (Beesigamukama et al., 2021). Regulations related to the use of insect ingredients for feed and food have changed, but were still ranked as important risks for feed and food producers. We believe that the recent new authorisations create further opportunities for business operators in European insect supply chains.

Stakeholders emphasised the importance of investing in new technologies to scale up production capacity and to ensure continuous high-quality production as an "operational" risk management strategy in all supply chain stages. This finding corresponds to the high scores on perceived risk regarding the lack of automation for rearers and its consequences for upscaling the production for feed producers. Respondents mentioned that these investments not only included financial investments in technology, but also in-house and project-related research and development. We also observed efforts to create more financial security and financial opportunities by ensuring access to funds or loans for companies. Again, this reflects the high perceived risks related to the lack of subsidies or finance.

Regarding further management of "financial, cost, and market" risks, we found that diversification strategies to mitigate for instance the high perceived supply and demand risks were not often applied across chain stages. Other strategies, such as obtaining insurance or buying or selling jointly, were also not widely applied. With regard to insurance, this could be related to the lack of available insurance specific for insect companies and/or to the low relevance that stakeholders ascribed to the lack of insurance. The use of insurance is suggested as an important risk management tool for smaller companies, but requires detailed knowledge on company risk and incurred costs (Falkner et al., 2015). Remarkably, only feed producers made frequent use of contracts to determine price and quality. This might be explained by the fact that larger companies, with a stronger representation in feed production, were more familiar with this strategy. "Regulatory" risk management strategies were not included in the survey since most regulatory restrictions represent external risks upon which business operators have little influence. Additional comments from stakeholders revealed that many of them continue to communicate, connect, and lobby with governments and associations to address these "regulatory" risks. These actions are in line with the suggestion of Marberg et al. (2017) for small companies to focus on collective lobbying operations.

***Actions needed by operators and third parties***

In general, it is important for both insect business operators as well as third parties to acknowledge that the nature and relevance of barriers and risks are different for individual actors and stakeholders. Hence, different actions could be taken by business operators and third parties in each of these supply chain stages. For rearers, efforts to mitigate risks should be channelled into automation techniques to reduce labour (costs) and into lowering of operational costs by using cheaper substrates (Heckmann et al., 2019). Capital is needed to make these investments in technologies and, therefore, the sector needs more legitimacy from finance providers. Furthermore, insect processors should mainly focus on the marketing of insect products, for instance by public education to improve social acceptance of insect-based products (Stull and Patz, 2020). To mitigate most relevant risks for insect-based feed producers, attempts should be made to realise a consistent quality and quantity of incoming insects or insect-based ingredients. Feed producers are rather dependent on rearing facilities in this regard, but the use of contracts could provide more certainty for large-scale feed producers. Insect-based food producers should primarily target a reduction of market and consumer risk. Most important in this regard is the improvement of social acceptance, including the collection of (sensory) data on insect-based food products to adapt products based on consumer preferences (Wendin and Nyberg, 2021). Eventually, forces of all supply chain actors should be bundled to facilitate further easing of regulations and create hereby a less uncertain regulatory landscape in Europe.



From the information collected through the survey, it was clear that intra-chain collaboration is not often practiced but regarded as essential for further development and scale up of the sector. In our view, collaboration in such an emerging sector is key to strengthen its financial position and increase resilience, especially for the commonly experienced barriers and risks. For third parties, including governmental agencies and financial institutions, initiating subsidy schemes, or enhancing access to finance would allow for more large-scale investments and increased production volumes. Furthermore, actions to facilitate authorisation procedures of new insect-based products would enable small insect businesses to expand their product range and increase sales on the food market.

***Limitations***

The representativeness of our results in view of the number and characteristics of the businesses operating in the different countries surveyed could not be estimated, since the exact number of operating companies is unknown. As Belgium, Germany, and the Netherlands are regarded as the sector's front-runners and are also best represented in our survey, we believe that we covered a relevant part of the sector. Furthermore, we recognise that the risk management strategies covered in this study mainly focused on business aspects and on the rearer stage, and not on marketing or other strategies commonly used more downstream in the supply chain. Even though including those could have enriched our results, the currently used strategies enabled us to compare across stages. In this regard, we believe to have covered relevant strategies to provide a first insight into risk management for insect businesses. Lastly, we realise that in comparing past barrier and future risk perception, the former has a larger certainty component compared to the latter. However, we believe that even though the scores have a slightly different certainty component, both are based on perception, which is eventually one of the main driving factors for behavioural change and decision-making when it comes to business and risk management strategies.

## 4.5 Conclusions

This chapter showed that most past barriers and future risks for insect operators were encountered or anticipated in the "finance, cost, and market" domain, particularly for insect processors. Other chain stages were also hampered by "regulatory" barriers and risks and – though to a smaller extent – "operational" ones. The highlighted barriers and risks included a lack of automation for large-scale rearing, the volatile demand for insect products, the limited access to finance and subsidies, and the constraints imposed by strict legislation. For rearers, perceived barriers and risks concerned those impacting profitability of businesses, specifically limitations to increase operational scale and lower operational costs by using cheaper substrates due to restrictions in legislation. Marketing barriers and risks, including low and volatile demand as well as limited social acceptance of insect-based (food) products, were especially important for processors and food producers, whereas price and quality of inputs were regarded as most constraining for feed producers. Regarding risk management, the most frequently applied strategies included investing in technologies with the aim of ensuring high and consistent quality of production, and this was true for all four chain stages. Based on our findings, we recommend to further enlarge opportunities for insect operators in obtaining finance for investments to enhance sector growth. Risk management should primarily focus on mitigation of "financial, cost, and market" risks. In addition, approval of alternative and possibly cheaper substrates as well as the authorisation of insect-based feed and food products should be further facilitated to enlarge sales and market opportunities.

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## Supplementary material

Supplementary material belonging to this chapter is available at: https://www.wageningenacademic.com/doi/suppl/10.3920/JIFF2022.0100/suppl_file/jiff2022.0100_esm.pdf

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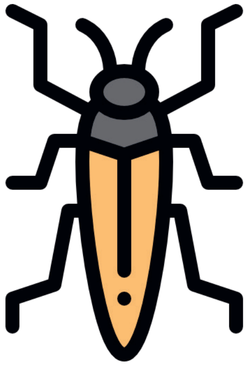

# 5

# Robustness of business models for insect production for feed and food in Europe

This chapter is based on the paper: Niyonsaba, H.H., Höhler, J., Rumpold, B.A., Van der Fels-Klerx, H.J., Meuwissen, M.P.M. Robustness of business models for insect production for feed and food in Europe. *Submitted to a journal.*

**Abstract**

Insects and their derivatives are increasingly recognised as a (more) sustainable and circular protein source for feed and food. The European insect industry is growing, but upscaling remains a challenge due to multiple uncertainties. This chapter analysed the robustness of three different business models for insect production for feed and food in six future scenarios. The three business models comprised: (1) full-liner *H. illucens* production for pet food, (2) decentralised *H. illucens* production for aquafeed, and (3) *T. molitor* processing cooperative for food. The six scenarios addressed uncertainties around the use of side streams, insect welfare, energy, and sustainability. We used the Business Model Stress Test in four focus groups with experts (n=23) from six European countries. Experts regarded full-liner *H. illucens* production for pet food and *T. molitor* processing cooperative for food as more robust than decentralised *H. illucens* production for aquafeed. These differences were mainly related to the *customer segments*, *value proposition*, *revenue structure*, and *cost structure.* The classification in relatively more or less robust business models serves as a guide for business and policy in further developing the insect sector for feed and food in Europe.

**Keywords:** Business Model Stress Test; robust business models; *H. illucens* production; *T. molitor* cooperative; scenario analysis for insect production

## 5.1 Introduction

Insect production for feed and food is generally considered as a sustainable and circular solution to meet growing protein demand (Henchion et al., 2017; Van Huis and Oonincx et al., 2017). The potential of insects lies in their ability to convert low-value streams into high-value proteins, the entire valorisation potential of mature larvae, and the minimal land-use requirements for production (Madau et al., 2020; Phi et al., 2020). Only in recent decades has insect production for feed and food started to emerge in Europe and gained interest from entrepreneurs and other experts. Nevertheless, the sector still faces considerable challenges in creating and scaling up viable business models (BMs) (Marberg et al., 2017; Niyonsaba et al., 2023a; Payne et al., 2019). The main barriers are existing regulations, high production costs, unstable demands, and low revenues (Niyonsaba et al., 2023a; Veldkamp et al., 2022). Recent years have shown an increase in large commercial investments and increased research funding (Marberg et al., 2017; Payne et al., 2019). These initiatives increased production volumes, stimulated the authorisation of the use of various insect species as food and feed (Lähteenmäki-Uutela et al., 2021; Rabobank, 2021), and generated more insight into economic performance (Niyonsaba et al., 2023b) thereby facilitating operators' access to credit and other services (Blanken et al., 2022). Although the European insect sector is thus becoming more solid, businesses still operate in dynamic and uncertain environments (Niyonsaba et al., 2023a).

Uncertainties in the agribusiness environment impede a business's ability to become competitive and achieve long-term sustainable development (Lezoche et al., 2020). A BM describes how a business can create and deliver (competitive) value in the context of turbulent and dynamic external environments (Dudin et al., 2015; Teece, 2010). Different ontologies can be used to visualise a BM design. All ontologies have in common that they consist of components that describe the targeted customer, the value proposition for this customer, the delivery of this value to the customer, and the revenues generated by this value creation and delivery (Teece, 2010). A BM is considered robust when it is technically feasible and economically viable in current and future (uncertain) environments (Haaker et al., 2017). While technical feasibility refers to the technical possibility of implementation, economic viability relates to generating positive financial results and the ability to maintain those results in the future (Haaker et al., 2017).

The developments in the European insect sector follow each other rapidly, creating positive future prospects. However, with the concurrent instability of many insect businesses, the questions arise of what the potential insect BMs are and which of these remain robust in uncertain future environments. While previous studies examined the circularity of different insect BMs (Madau et al., 2020; Phi et al., 2020), a structural assessment of BM components is lacking.

In this chapter, we explore three potential BMs for European insect production and examine their robustness by applying a Business Model Stress Test (BMST) (Haaker et al., 2017) in four focus groups. We first assess and describe the robustness of three BMs in six identified scenarios separately. We then compare the robustness of the three BMs with the aim of identifying their main commonalities and differences. This enables us to identify the relatively most robust BMs for insect production for feed and food in Europe and reveal the underlying factors that influence their robustness. The BMs comprise two models for *H. illucens* (black soldier fly (BSF)) and one for *T. molitor* (yellow mealworm (mealworm)) production[12]; these are species that are considered suitable for insect production for feed and food in Europe (Francuski et al., 2020). The considered BMs include the stages of the chain from reproduction or production of larvae to the delivery of a processed product. Robustness is assessed for scenarios that capture sector concerns about side-stream regulations, insect welfare regulations, and sustainability requirements and energy prices.

This chapter has two main contributions. First, in the domain of insect production, the structured identification and assessment of BMs add a business perspective to the already much wider developed technical knowledge, as summarised in Smetana et al. (2021) and Veldkamp et al. (2021). Second, in the BM domain, the contribution is in the application of BMST to not yet existing BMs in an emerging agricultural sector. The results can be used by (starting) insect rearers for decision-making on BM design and innovation, and by experts and governing bodies as a basis for strategic planning or intervention design to stimulate the development of the insect sector.

## 5.2 Material and methods

### *Six steps of the Business Model Stress Test*

The BMST (Haaker et al., 2017) assesses the robustness of BMs and enables identifying opportunities and threats for specific BMs. The method follows a sequence of six steps (Haaker et al., 2017): (1) description of the BM, (2) identification and selection of stress factors or uncertainties, (3) exploration of the relationship between uncertainties and BM components, (4) creation of a heat map, (5) analysis of results, and (6) formulation of improvements and actions. We did not incorporate the sixth step as part of the BMST; instead, we discuss possible improvements and actions in the discussion section of this chapter.

### *Step 1: Description of business models through expert elicitation*

Similarly to Haaker et al. (2017), we used the Business Model Canvas to describe the BMs, as this is the most popular ontology in practice. The three types of BMs were selected

[12]In this chapter ‘black soldier fly’ refers to the species *H. illucens* and ‘mealworm’ refers to the species *T. molitor.*

based on relevant literature (Le Feon et al., 2019; Niyonsaba et al., 2023a; Saatkamp et al., 2022) together with the experience of the authors from previous research and interactions with experts. The three identified BMs comprised: (1) full-liner BSF production for pet food, (2) decentralised BSF production for aquafeed, and (3) mealworm processing cooperative for food. Detailed descriptions of these BMs in the European context were then developed together with experts (n=5) who had long-standing experience in the insect industry or as consultants. Interviews were held in January and February 2023 with experts from Denmark, Italy, Portugal, Spain, and the Netherlands, identified through the network of the first author. Consent was signed before the start of the online interviews, and all interviews followed a similar structure. Experts were asked to describe the BM following the Business Model Canvas ontology and to elaborate on each BM component as complete as possible. BMs eventually differ with regard to ownership, geographical concentration, scale of production, degree of mechanisation, and the chain stages covered (Table 5.1). A description of the BM components of each BM follows hereafter.

*Table 5.1 Overview of characteristics per business model.*

| | Ownership | Geographical concentration | Scale of production | Degree of mechanisation | Chain stages |
|---|---|---|---|---|---|
| **Full-liner BSF production for pet food** | Individual | Centralised | Large scale | High | Reproduction, production, processing |
| **Decentralised BSF production for aquafeed** | Individual | Decentralised | Large scale | High | Reproduction, production, processing |
| **Mealworm processing cooperative for food** | Cooperative members | Decentralised | Small-scale production, large-scale processing | Low | Production, processing |

The *full-liner BSF production for pet food* is a large-scale BSF facility in which reproduction, production, and processing are centralised at one location (Table 5.1). The main side streams as input for production are purchased from the food industry and sourced from distant locations (Figure 5.1). A high quality of side streams is required to guarantee optimal quality of the end product: a sustainable hypoallergenic ingredient for pet food (i.e. larvae meal and oil). Additional resources for production include a starter colony for BSF larvae, utilities, and skilled labourers. The main activities involve the fully mechanised rearing and processing of BSF larvae, as well as the development and marketing of end products. To build a long-term, loyalty-based relationship with customers (pet food producers) for a high level of consumer (pet owners) satisfaction, this BM puts emphasis on high quality, marketing, and product development. This, among others, materialises by involving pet food producers in product development through co-creation. The core target market is the pet food market, in which consumers value high

Chapter 5

quality over low price. The end products of the full-liner facility include larvae meal, insect oil, and insect frass. The former two products are sold to pet food producers, and the latter to a digester. The major production expenses include labour, side-stream procurement, utilities, and quality assurance.

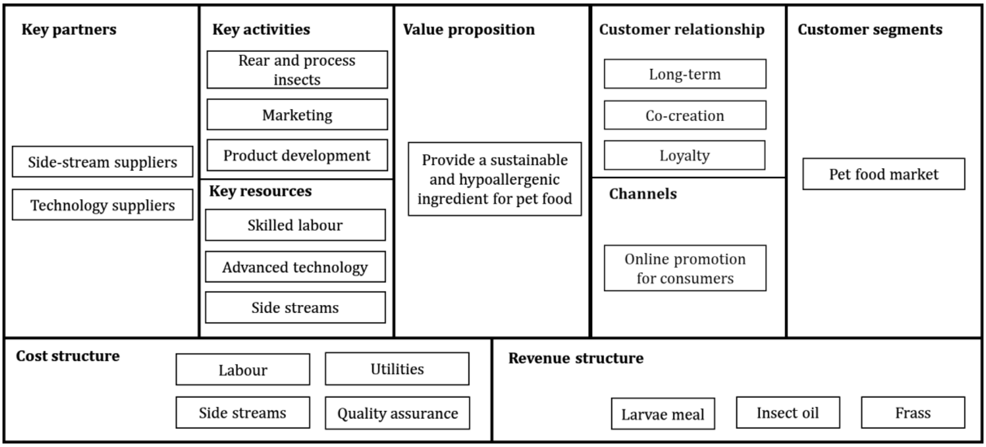


*Figure 5.1 Business Model Canvas for full-liner BSF production for pet food.*

*Decentralised BSF production for aquafeed* is a large-scale production and processing system, which is excecuted at different locations, including a reproduction facility, multiple rearing facilities, and one processing unit (Table 5.1). All processes are mechanised, necessitating the use of advanced technologies (Figure 5.2). In addition, an advanced logistic network optimises frequent transport between reproduction, rearing, and processing locations. The main side streams for production come from the food industry and are sourced in close proximity to the rearing locations. The food industry pays the rearer for offtake of side streams; these side streams have high quality variations. The value proposition of this BM is the processing of side streams and the simultaneous production of a sustainable aquafeed ingredient. The relationship with customers – side-stream suppliers and aquafeed producers – is based on long-term contracts. The end consumers in this BM are individuals who purchase fish products, while the fish are fed with insect-based aquafeed. The revenue model is two-sided: on the one hand, the rearer is paid for the offtake of side streams; on the other hand, revenues come from the sales of larvae meal for aquafeed and, to a small extent, from sales of frass.

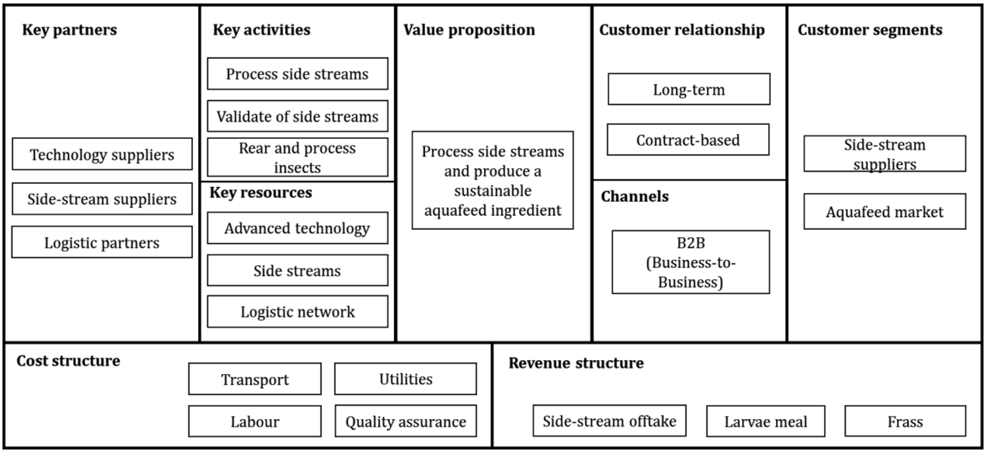


*Figure 5.2 Business Model Canvas for decentralised BSF production for aquafeed.*

*The mealworm processing cooperative for food* is a BM with multiple rearing sites, and one processing facility (Table 5.1). Young larvae from reproduction, dry substrates, and side streams are purchased by the rearer who also manages the rearing operations, mostly with a low level of mechanisation (Figure 5.3). Processing and frass hygienisation are organised by the cooperative. The key activities for this BM include the rearing and processing of mealworms, cooperative and logistics management, and quality control. The value proposition of the mealworm processing cooperative is to process mealworms into an intermediate product which could be incorporated into food products. The relationship with customers, (i.e. food producers), is contract-based and characterised by high transparency and a high level of information sharing. The end consumers of this BM are individuals who purchase insect-based food products. The main revenues come from the sales of the intermediate processed food product, and, to a lesser degree, from the sales of frass.

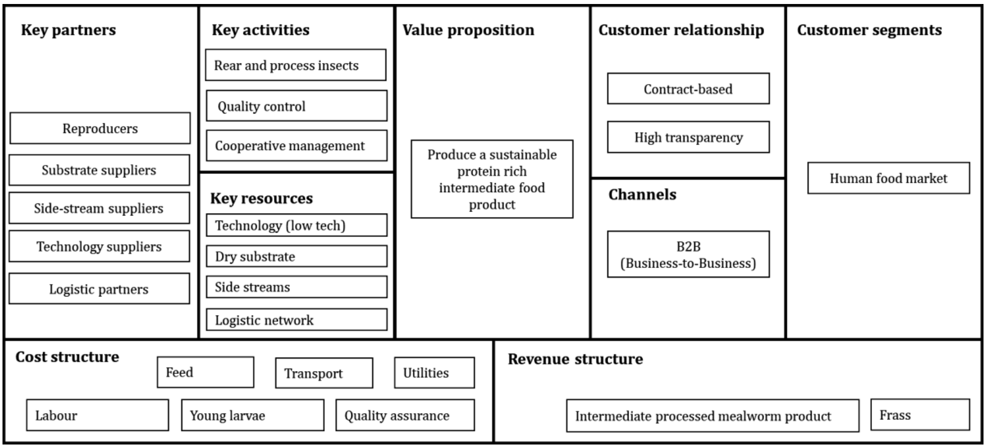


*Figure 5.3 Business Model Canvas for a mealworm processing cooperative for food.*

### *Step 2: Identification and selection of stress factors or uncertainties*

Where Haaker et al. (2017) made use of single factor uncertainties (so-called stress factors) we chose for more elaborate descriptions. Uncertainties were elicited with experts (n=7) who were selected in a similar way as in Step 1. Three experts could cover both steps. For these experts, interviews for Step 1 and Step 2 were combined. The interviews for Step 2 also took place in January and February 2023. *During the interviews,* experts were asked to mention two or three potential uncertainties for each of the components (political, economic, social, technical, legal, and environmental) of the PESTLE framework (Perera, 2017). This framework is often used to analyse factors impacting the business environment; see e.g. Widya Yudha et al. (2018). Expertise differed among experts and some components of the framework remained unanswered in case experts did not feel confident to elaborate on these. The final list of uncertainties was selected by the authors on the basis of indicated relevance to the three BMs.

The uncertainties were categorised into three types, each of which exhibited two manifestations. The six resulting scenarios (1.A–3.B) are described in Table 5.2, together with their short names. For pragmatic reasons, the third uncertainty type merges two uncertainty issues, i.e. sustainability requirements and energy prices.

*Table 5.2 Description of uncertainties and scenarios. Short names are in brackets.*

| | **Scenario A**[1] | **Scenario B**[1] |
|---|---|---|
| **Uncertainty 1**<br>Regulations on the use of side streams | Regulations become more liberal, allowing the use of non-certified side streams; this increases their availability, but product safety becomes a concern.<br>(*Liberal side-stream regulations*) | Current regulations on the use of side streams remain; this keeps the available amount low, but product safety is of lesser concern.<br>(*Strict side-stream regulations*) |
| **Uncertainty 2**<br>Insect welfare regulations | Insect welfare is not regulated by law, increasing consumer concerns about insect welfare.<br>(*No insect welfare regulations*) | Insect welfare is strictly regulated, reducing consumer concerns about insect welfare.<br>(*Strict insect welfare regulations*) |
| **Uncertainty 3**<br>Sustainability requirements & energy prices | There are no specific requirements for sustainability. Energy prices continue to increase.<br>(*No specific sustainability requirements; increasing energy prices*) | Businesses must comply with sustainability requirements. Energy prices remain stable.<br>(*Comply with sustainability requirements; stable energy prices*) |

[1] As presented to the participants

Uncertainty 1: Regulations on the use of side streams

Since authorised side streams are limited to GMP+ streams, side streams are currently a major and costly input for insect production (Van Peer et al., 2021). To reduce costs and increase availability of side streams, and improve circularity of insect production, the use of additional side streams (such as catering waste) will be crucial for its viability., implying that side-stream regulations should change (Broeckx et al., 2021). However, a lack of standardisation and scientific evidence on the safe use of these side streams limits the likelihood of changes in the regulations (Meyer et al., 2021).

Uncertainty 2: Insect welfare regulations

Currently, there are few official species-specific regulations on the welfare of insects. This is mainly due to the lack of conclusive evidence, particularly regarding the sentience of insects (Barett et al., 2022; Delvendahl et al., 2022). Most of the literature has focussed on the importance and difficulty of obtaining scientific data on insect welfare aspects, but new insights can become available and significantly impact industry operations (Barett et al., 2022). Delvendahl et al. (2022) concluded in their recent publication that the predicted growth of the insect industry and increasing consumer concerns for animal welfare require regulations specified per species and production stage.

Uncertainty 3: Sustainability requirements & energy prices

The environmental footprint of livestock production is under pressure (Borodin et al., 2016). Although insect production is believed more sustainable compared to other livestock production systems, the high energy use of insect production and processing is still an environmental concern (Smetana et al., 2021). Data and benchmarks on the environmental sustainability of insect production systems and end products are limited. However, these data are crucial for evaluating the sustainability of insect production systems (Wade and Hoelle et al., 2020). There is a chance that governments will enforce compelling measures for companies to reduce their environmental impact in order to enhance their sustainability. Moreover, energy costs have seen a drastic rise in the last two years. The energy-intensive nature of insect production systems could result in economically unfavourable conditions (Van der Weele et al., 2019).



***Step 3: Exploration of relationship between uncertainties and BM components***

This is an intermediate step in which direct and indirect causal relationships between uncertainties and BM components are explored. It serves as an evaluation to confirm that described scenarios are related to the (majority of) BM components. This step was carried out by the first author. It helped to prepare for the focus groups (Step 4).

***Step 4: Creation of heat maps***

This step assesses how scenarios are expected to affect the BM components. The impact assessment was conducted through four focus groups: one in Belgium (n=5), one in Germany (n=7), one in the Netherlands (n=6), and one in Southern Europe (n=5). Across focus groups, there were five experts from Belgium, six from Germany, three from Italy, seven from the Netherlands, one from Portugal, and one from Switzerland. The choice for these countries was primarily based on the network of the authors. Each focus group consisted of experts from the insect industry, consulting, and research. The BMs were assigned to a group based on the expertise of the experts with the different insect species.

Each focus group addressed one or two BMs, eventually leading to the *full-liner BSF for pet food* production assessed in the German and Southern European focus group, the *decentralised BSF production for aquafeed* in the Dutch focus group, and the *mealworm processing cooperative for food* in the German and Belgian focus group. The focus groups took place in February and March 2023 and lasted approximately two hours each. During this period, there were no insect-related crises or major policy changes affecting the insect sector. Focus groups were hybrid (n=2), physical (n=1), or online (n=1); all were recorded for data analysis purposes. Before joining the focus groups, participants received preparatory information on the discussed BM(s) and an overview of the related supply chain(s)[13]. Consent was signed prior to the focus groups and the sessions started with a detailed explanation on the assessment, the discussed BM(s) and scenarios. Then the participants were given time to rate the impact of each scenario on each BM component described in a pre-designed Excel sheet (on PC or printed version).

During the assessment, one of four colours (representing different impacts) could be selected: green, orange, red, or grey, representing 'no negative impact' or 'possibly positive impact', 'requires attention', 'show-stopper' or 'not relevant', respectively – see also Table 5.3. Detailed instructions given to participants regarding these colours are displayed in the Supplementary material (S.2.1).

*Table 5.3 Explanation of the colours used in the impact assessment, based on Haaker et al. (2017).*

| Colour | Description | Required or action consequences | Impact of the scenario on the technical feasibility and/or economic viability of a specific BM component[1] |
|---|---|---|---|
| *Green* | 'No negative impact' or 'possibly positive impact' | Not applicable | This scenario affects the technical feasibility or economic viability of the BM component, but not in a negative way – possibly even in a positive way. |
| *Orange* | Requires attention | Revisit choices BM on component | This scenario makes the BM component no longer economically viable. |
| *Red* | Show-stopper | Can become a show-stopper for the BM | This scenario makes the BM component no longer technically feasible. |
| *Grey* | Not relevant | Not applicable | This scenario does not affect the BM component. |

[1]Business model components include: key partners, key activities, key resources, value proposition, customer relationships, channels, customer segments, cost structure, and revenue structure.

After filling out the assessment, participants were asked to elaborate on their impact ratings for each scenario. The moderator (first author) asked deepening questions to better understand the given impact rating and its context, and invited participants to reflect on the reasoning of other participants. Due to time limitations, not all BM components could be discussed for each scenario.

[13]The preparatory information on the discussed BM(s) and an overview of the related supply chain(s) can be found in the Supplementary material (S.1.1-S.1.3).

***Step 5: Analysis of results***

The assessment sheets were collected from each participant (some of whom added written explanations) and recordings of the meetings were manually transcribed. Heat maps, in which colours are indicative of impact ratings, were created based on impact ratings of the scenarios on the BM components. For each cell in the matrix (i.e. an impact of one scenario on one BM component), the frequency of the colours green, orange, red, or grey was counted, representing the number of participants from the total group who indicated a colour for this cell. Of these, the colour with the highest frequency, i.e. the mode, was then selected for each cell, resulting in the final heat map. If a cell had two colours, both of which had the highest frequency, the cell was assigned two colours. The number of experts rating the mode and the total number of experts for this BM are displayed in each cell in the heat map. Not all participants were able to provide an impact estimate for all cells, therefore the sample size *n* differs per cell. In describing the underlying reasons for the chosen impact ratings, we focus on the BM components that provoked the most discussion in the group. Conclusions on the relative robustness of BMs are drawn on the basis of the percentage of coloured components. For instance, a BM with the most orange and red coloured components is regarded as the least robust.

## 5.3 Results

The following sections include the heat maps for the three BMs with the underlying reasons for the given impacts in each heat map. The BM components are indicated in italics; the uncertainty (numbers 1–3) or the scenario (alphanumeric 1.A–3.B) are enclosed in brackets and correspond to the numbering in the figures (see figures 5.4–5.7 for heat maps). The most relevant differences and commonalities between BMs per scenario are highlighted.



***Heat maps per business model***

<u>Full-liner BSF production for pet food</u>

Strict side-stream and insect welfare regulations (1.B and 2.B) were considered to have a positive impact on BM components of the full-liner BSF production for pet food (Figure 5.4). On the contrary, liberal side-stream and absent insect welfare regulations (1.A and 2.A) were expected to have a negative impact on its BM components. The energy and sustainability scenarios (3.A and 3.B) appeared to be less relevant to the majority of BM components.

*Uncertainty 1.* When discussing the expected impacts of regulations on the use of side streams, experts perceived that including non-certified side streams (only possible under liberal regulations – 1.A) would enhance resource utilisation. This could increase the circularity of production, leading to an improved *value proposition* (1.A). However, including these non-certified side streams was also expected to result in a large variety of side streams (type, safety, and quality). Such a large variety requires different *key* *resources* and *partnerships* for operations and technologies (e.g. on pretreatment of side streams). Additionally, these non-certified side streams were expected to introduce risks for quality and safety variations of the end product, which negatively impact the *value proposition*, and complicate sales in the *customer segment* of the pet food market leading to lower *revenues*. Under strict side-stream regulations (1.B), experts expected a low availability of certified side streams that would push prices up, resulting in a negative impact on the *cost structure* of the BM. Moreover, this low availability was further projected to impede upscaling of an insect businesses and their realisation of economies of scale with existing side-stream suppliers. Despite these constraints, experts foresaw that the implementation of strict side-stream regulations (1.B) will lead to an increase in consumer trust, potentially resulting in a positive impact on the *revenue structure* through higher sales. Experts agreed that pet owners (*consumers*) in the *customer segment* of the pet food market are generally selective in their product choice and willing to pay more for a high-quality product, which could explain the experts' indicated preference for the scenario of strict regulations (1.B).

*Uncertainty 2.* The plenary discussion on insect welfare revealed that the absence of regulations (2.A) was expected to negatively impact most BM components, mainly due to the welfare concerns of pet owners driving market contraction with subsequent negative impacts on the *revenue structure*. Strong *customer relationships* and marketing strategies with a high level of consumer (i.e. pet owners) education would be necessary to gain their trust with respect to insect welfare. Experts agreed that implementing strict insect welfare regulations would enhance the trust of pet owners and the *value proposition*, consequently leading to a positive impact on pet food sales. However, they acknowledged that strict welfare regulations also have negative aspects. Specifically, high costs for the implementation of *key resources* such as new technologies and quality systems to comply with these regulations (2.B) were expected to adversely impact the *cost structure*. Experts eventually agreed that in both scenarios (2.A and 2.B), the sector should not wait for regulations to be implemented by governmental bodies but instead use a pro-active sectoral approach in developing insect welfare standards.

*Uncertainty 3.* Although the scores in the heat map mostly indicated that sustainability requirements and energy prices were not perceived as relevant, experts discussed that raising energy prices (3.A) would increase production costs (*cost structure*), possibly resulting in nonprofitable business cases. They further expected that compliance with sustainability requirements (3.B) would require necessary changes in *key resources*, including high capital investments for technology adaptations, which also have negative impacts on the *cost structure*. At the same time, compliance with sustainability requirements (3.B) could result in positive sustainability evaluations of products that support marketing messages, positively impacting product sales. This would then likely lead to increased market shares and revenues (*revenue structure*). However, experts indicated that data on sustainability of insect production are still scarce and that clear comparisons with competitive products in similar market segments are essential to construct such marketing messages.

| Full-liner BSF production for pet food | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Business Model Canvas component ↓** | **Uncertainty →** | **1. Regulations on the use of side streams** | | **2. Insect welfare regulations** | | **3.Sustainability requirements and energy prices** | |
| | **Scenario →** / **Business model component ↓** | **1.A** Liberal side-stream regulations | **1.B** Strict side-stream regulations | **2.A** No insect welfare regulations | **2.B** Strict insect welfare regulations | **3.A** No specific sustainability requirements. Increasing energy prices | **3.B** Comply with sustainability requirements. Stable energy prices |
| **Customer segment** | Pet food | 6/11 | 7/10 | 7/11 | 10/11 | 5/10 | 6/11 |
| **Customer relationship** | Long-term, co-creation, loyalty | 7/11 | 6/10 | 8/11 | 9/11 | 4/10 4/10 | 5/11 5/11 |
| **Channels** | Online promotion for consumers | 6/11 | 4/10 4/10 | 6/11 | 10/11 | 5/10 | 5/10 |
| **Value proposition** | Sustainable hypoallergenic pet food ingredient | 5/11 | 7/11 | 3/10 3/10 | 8/10 | 4/11 | 6/11 |
| **Key activities** | Marketing, product development | 6/11 | 6/10 | 5/10 | 8/11 | 4/10 | 4/10 |
| **Key resources** | Skilled labour, technology, side streams | 5/11 | 7/11 | 5/11 | 5/11 | 6/10 | 6/11 |
| **Key partnerships** | Side-stream suppliers, technology suppliers | 7/11 | 4/10 4/10 | 6/10 | 5/10 | 6/10 | 7/10 |
| **Revenue structure** | Larvae meal, insect oil, frass | 5/11 5/11 | 7/10 | 6/10 | 8/10 | 4/10 | 4/10 |
| **Cost structure** | Labour, utilities, side streams, quality assurance | 5/11 | 4/10 | 5/10 | 8/11 | 7/11 | 5/11 |

<u>**Legend**</u>
- 'No negative impact' or 'possibly positive impact'
- Requires attention
- Show-stopper
- Not relevant

*Figure 5.4 Heatmap for full-liner BSF production for pet food, showing the impact of six scenarios (1.A-3.B) on nine business model components. Numbers in the coloured cells indicate number of given responses for this colour divided by the total number of respondents for this business model. Cells with two colours indicate these both had similar highest frequency.*



## <u>Decentralised BSF production for aquafeed</u>

Overall, the heat map of the decentralised BSF production for aquafeed does not show a clear difference among the expected impacts of scenarios (i.e. between A and B scenarios)

(Figure 5.5); most BM components require attention. An exception can be found in sustainability requirements and energy prices, where compliance and more stable prices (3.B) appear to have a more positive influence.

*Uncertainty 1.* When discussing regulations on the use of side streams, experts expected that liberal regulations (1.A) would increase side-stream availability, but also cause large quality variations in the side streams, produced insects, and the end products. These variations were estimated to negatively impact the *value proposition* and *revenue structure*. Experts further elaborated that food safety risks increase with liberal regulations (1.A), putting the reputation of the sector at stake and requiring strong *partnerships* to prevent deviations in product safety and quality. They also stressed that quality assurance is extremely important for *customer relationships* and stable *revenues* within the sector. Experts further emphasised that liberal side-stream regulations (1.A) call for strong intra- and inter-sectoral collaborations to achieve operational feasible solutions. If implemented well, large (economic) opportunities would open up for creating viable business cases. Therefore, the increased availability of side streams under liberal regulations was expected to reduce costs and facilitate the upscaling of BSF production (1.A). Regarding the *revenue* and *cost structure*, experts agreed that relying on revenues for the offtake of side streams would be risky under liberal (1.A) and unfeasible under strict side-stream regulations (1.B). In the former case, it might be only feasible with long-term fixed contracts and robust partnerships. Under strict regulations (1.B), the main concerns included the low availability of the side stream that prevents the execution of viable business cases and the opportunities for upscaling to become competitive in the aquafeed market (*customer segment*). Most experts further expected that the use of certified side streams benefits consumer trust and, thereby, sales (*revenue structure*). However, some experts felt that this benefit is not so pronounced and that fish consumers are less concerned about how the BSF that are part of the fish's diet are fed.

*Uncertainty 2.* Experts expressed different concerns regarding BSF welfare: some did, while others did not consider this to be relevant for fish consumers (*customer segment*). Experts indicated that if consumer concerns about insect welfare arise, these concerns likely reduce market share and subsequently *revenues*, necessitating strong *customer relationships*. However, the majority of experts agreed that insect welfare regulations are essential to standardise BSF production to prevent large variations in production methods between companies (2.B). Implementing welfare regulations also requires potential adjustments in *key activities* and *resources* for individual businesses. Considering new methods or techniques (*key resources*) that are to be implemented to comply with insect welfare regulations, experts indicated that the size of additional investments (*cost structure*) and the extent of operational adjustments (*key activities*) are hard to quantify at the moment of the focus group discussion. They further concluded that a pro-active approach initiated by the sector and good collaboration with governmental bodies are crucial to deal with consumer concerns for insect welfare.

*Uncertainty 3.* Discussions on sustainability requirements and energy prices revealed that rising energy prices (3.A) increase cost-prices (*cost structure*), which is considered a general threat for viable business cases and becomes a show-stopper in this BM. Hence, the increase of cost-prices (*cost structure*) would inevitably result in higher sales prices (*revenue structure*), likely leading to lower sales. From a supply chain perspective, the implementation of sustainability requirements (3.B) could have a positive impact on the BM in general. These requirements could improve sustainability evaluations of production and the end products, resulting in a more positive *value proposition*. However, sustainability evaluations were mentioned to depend on the factors considered in environmental impact calculations. In this regard, experts agreed that a clear framework on sustainability measures for the insect industry in general is a key requirement, and that current sustainability data are insufficient to build standardisations for the BSF and wider insect industry.

| Decentralised BSF production for aquafeed | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Business Model Canvas component ↓** | **Uncertainty →** | **1. Regulations on the use of side streams** | | **2. Insect welfare regulations** | | **3. Sustainability requirements and energy prices** | |
| | **Scenario →** / **Business model component ↓** | **1.A** Liberal side-stream regulations | **1.B** Strict side-stream regulations | **2.A** No insect welfare regulations | **2.B** Strict insect welfare regulations | **3.A** No specific sustainability requirements. Increasing energy prices | **3.B** Comply with sustainability requirements. Stable energy prices |
| **Customer segment** | Side-stream producers, aquafeed | 4/7 | 3/7 | 3/7 | 3/7 | 4/7 | 3/7 |
| **Customer relationship** | Long-term, contract-based | 3/7 3/7 | 3/7 | 3/7 | 4/7 | 4/7 | 3/7 |
| **Channels** | B2B (Business-to-Business) | 4/7 | 3/7 | 3/7 | 3/7 | 4/7 | 3/7 |
| **Value proposition** | Process side streams and produce a sustainable aquafeed ingredient | 6/7 | 2/7 2/7 | 3/7 | 3/7 | 3/7 | 3/7 |
| **Key activities** | Process side streams, validate side streams, rear and process insects | 4/7 | 3/7 3/7 | 3/7 3/7 | 3/7 | 4/7 | 3/7 3/7 |
| **Key resources** | Advanced technology, side streams, logistic network | 3/7 | 4/7 | 3/7 | 5/7 | 4/7 | 3/7 3/7 |
| **Key partnerships** | Technology suppliers, side-stream suppliers, logistic partners | 3/7 3/7 | 5/7 | 4/7 | 3/7 3/7 | 3/7 | 3/7 3/7 |
| **Revenue structure** | Side-stream offtake, larvae meal, frass | 3/7 3/7 | 3/7 | 3/7 | 2/7 2/7 | 4/7 | 4/7 |
| **Cost structure** | Transport, labour, utilities, quality assurance | 4/7 | 4/7 | 4/7 | 4/7 | 3/7 | 3/7 |

**Legend**
'No negative impact' or 'possibly positive impact' — Requires attention — Show-stopper — Not relevant

*Figure 5.5 Heatmap for the decentralised BSF production model for aquafeed, showing the impact of six scenarios (1.A–3.B) on nine business model components. Numbers in the coloured cells indicate number of given responses for this colour divided by the total number of respondents for this business model. Cells with two colours indicate these both had similar high frequency.*

Mealworm processing cooperative for food

In general, the heat map for the mealworm processing cooperative for food shows that strict regulations or set requirements (B scenarios) are in general not expected to negatively impact the BM components (Figure 5.6). Conversely, liberal or absent regulations and requirements (A-scenarios) require attention and even include a few show-stoppers.

*Uncertainty 1.* When discussing the regulations on the use of side streams, experts highlighted that liberal side-stream regulations (1.A) present opportunities to utilise more low-value side streams. This potentially enhances the circularity of production, which positively influences the *value proposition*. However, the use of low-value side streams - often not certified - was also anticipated to pose a serious threat to sales on the human food market (*customer segment*). The foreseen threat was attributed to reasons such as low consumer acceptance due to insufficient transparency on side-stream use, as well as elevated food safety and quality risks. Experts further emphasised that significant quality variations in both side streams and mealworms could present a substantial challenge for processors in achieving a marketable end product with a consistent nutritional profile and product quality. Experts acknowledged that a processing cooperative – given good cooperations and *partnerships* between its members - is in a strong position to control food safety. They also expected that the use of a larger side-stream variety (1.A) requires rearers and processors to make additional investments in *key resources*, including new technologies with high capital *costs*. The increase in the availability of side streams due to liberal regulations was expected to lower the price of side streams (1.A). However, the cost benefits of using cheaper side streams were expected to be small due to the relatively low possible share of side streams in mealworm feed. Increasing this share may require changes in farm operations (*key activities*). Therefore, experts agreed that strict regulations (1.B) would benefit mealworm production, the main reason being the quality and safety of the product for the *customer segment* human food market. Apart from the strict regulations for side streams (1.B) being more beneficial, experts were concerned about the low availability of side streams (*key resources*). Without a sufficient amount of input, the growing demand for insects for food cannot be met.

*Uncertainty 2.* Discussions on insect welfare disclosed that the absence of insect welfare regulations (2.A) could result in high consumer concerns, complicating sales and a negative impact on the *revenue structure*. Experts indicated that, even without insect welfare regulations, businesses should prioritise insect welfare by changing *key activities* such as greater chain coordination, quality control, and technology changes. They further agreed that the sector should proactively take initiative in consumer education and communication (*customer relationship* and *channels*) to inform consumers (i.e. food consumers) and show transparency about insect welfare. Hence, experts expected that strict insect welfare regulations (2.B) would benefit businesses due to increased consumer trust. However, they indicated that the design and implementation of insect welfare regulations require close collaboration with regulatory bodies. The experts also expected large challenges due to the investments required for technology adjustments (*key resources*) to comply with insect welfare regulations. Overall, they concluded that, considering the young and emerging nature of the sector, a strong focus on transparency and prevention of scandals with regard to insect welfare is key.

*Uncertainty 3.* In the discussions on sustainability requirements and energy prices, some experts indicated that the rising energy prices (3.A) would cause great concerns for the utilities component in the *cost structure*. However, certain experts highlighted that the low degree of mechanisation leads to a relatively modest increase in energy costs compared to highly mechanised facilities. Furthermore, costs for transport were expected to be lower than those for central facilities due to the closer proximity of side-stream sourcing options for more dispersed mealworm production sites. The implementation of sustainability requirements (3.B) was generally regarded positive. Also, there was general consensus that more data and frameworks are needed for correct sustainability standardisations and calculations.

| Mealworm processing cooperative for food | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Business Model Canvas component ↓** | **Uncertainty →** | **1. Regulations on the use of side streams** | | **2. Insect welfare regulations** | | **3. Sustainability requirements and energy prices** | |
| | **Scenario →** / **Business model component ↓** | **1.A** Liberal side-stream regulations | **1.B** Strict side-stream regulations | **2.A** No insect welfare regulations | **2.B** Strict insect welfare regulations | **3.A** No specific sustainability requirements. Increasing energy prices | **3.B** Comply with sustainability requirements. Stable energy prices |
| **Customer segment** | Human food market | 6/12 | 8/10 | 5/10 \| 5/10 | 8/11 | 5/10 | 6/10 |
| **Customer relationship** | Contract-based, high transparency | 11/12 | 6/10 | 10/11 | 8/11 | 3/8 \| 3/8 | 4/9 |
| **Channels** | B2B (Business-to-Business) | 5/10 | 6/10 | 4/9 | 7/10 | 3/8 \| 3/8 | 5/9 |
| **Value proposition** | Produce a sustainable protein rich intermediate food product | 6/11 | 6/10 | 6/10 | 6/10 | 3/10 \| 3/10 | 5/10 |
| **Key activities** | Rear and process insects, quality control, cooperative management | 8/11 | 8/10 | 5/10 | 6/10 | 6/9 | 5/9 |
| **Key resources** | Technology (low tech), dry substrate, side streams, logistic network | 5/11 | 5/10 | 4/9 | 4/9 | 5/11 \| 5/11 | 5/9 |
| **Key partnerships** | Technology suppliers, substrate suppliers, reproducers, logistic partners | 5/11 | 7/10 | 4/10 \| 4/10 | 4/10 | 5/11 | 6/9 |
| **Revenue structure** | Intermediate processed mealworm product, frass | 6/10 | 5/10 | 4/8 | 5/9 | 6/10 | 7/9 |
| **Cost structure** | Feed, labour, transport, young larvae, utilities, quality assurance | 8/11 | 5/10 | 10/10 | 9/11 | 7/11 | 6/11 |

**Legend**
- ‘No negative impact’ or ‘possibly positive impact’
- Requires attention
- Show-stopper
- Not relevant

*Figure 5.6 Heatmap for the mealworm processing cooperative for food, showing the impact of six scenarios (1.A–3.B) on nine business model components. Numbers in the coloured cells indicate number of given responses for this colour divided by the total number of respondents for this business model. Cells with two colours indicate these both had similar high frequency.*

### *Comparison of robustness across business models*

When examining the scenarios (1.A–2.B) linked to the uncertainty of regulations (1 and 2) (top and middle part of Figure 5.7), it becomes evident that strict legislation was considered advantageous for the BMs for pet food and food, primarily due to its positive effect on consumer trust (Figure 5.7). This picture is generally the opposite for the BM for aquafeed; the use of side streams as feed for insects and the requirements on insect welfare seemed to have less impact on the perceptions and sales of the final marketable product (i.e. the fish) of the aquafeed BM. This reduces the direct need of these regulations to ensure consumer trust and sales for the aquafeed market. In addition, the heat map (bottom part of Figure 5.7) for sustainability requirements and energy prices (3.A and 3.B) reveals that high energy prices (3.A) were expected to negatively impact all BMs, especially their *cost structure*, for which these high prices are considered a show-stopper. Compliance with sustainability requirements (3.B) was generally considered positive for the BMs. Improved compliance with sustainability requirements was expected to benefit the *value proposition* of all BMs.


*Figure 5.7 Heatmaps for three business models (in columns), showing the impact of six scenarios (1.A-3.B) on their nine business model components. Cells with two colours indicate that there were two impacts with equal frequency.*

## 5.4 Discussion

This chapter is the first to structurally assess the robustness of BMs for European insect production: *full-liner BSF production for pet food, decentralised BSF production for* *aquafeed*, and *mealworm processing cooperative for food*. Robustness was evaluated for six scenarios with varying uncertainties.

***Robustness of business models***

When examining the results across the BMs, we identified several factors that affect the robustness of the investigated BMs for insects as food and feed. The *customer segment* emerges, for instance, as a significant component for BM robustness, with BMs producing for the pet food and human food market exhibiting relatively greater robustness compared to those producing for the aquafeed market. Most of the experts in our study had experience in the insect sector, with some having expertise in food and pet food production, but none had direct involvement in aquafeed production. Although they also had knowledge of the aquafeed sector from collaborations, the absence of specific experience in this market may have influenced the results for the BM component of *customer segments,* impacting overall BM robustness. Concurrently, we assessed the robustness of BMs based on perceptions of experts from different regions, since we did not want to exclude specific regions (i.e. northwest and southern Europe). The level of development and (legal) conditions of the sector differed between the two regions and sometimes even between countries. Even though a few experts from Southern Europe had more positive expectations on side-stream availability and foresaw less problems on insect welfare, we did not observe substantial variations in the robustness impact assessment between focus groups. Although we acknowledge that variations in expertise and geographical location may have slightly influenced impact estimation in the robustness assessment, we believe that they did not affect the interpretation of BM descriptions and scenarios. This might be attributed to the fact that we provided the experts with clear explanations and repeatedly enquired for questions and clarity prior to and during the robustness assessment. Furthermore, three uncertainties (with six scenarios) were selected for the robustness assessment based on expert input (interviews). By doing so, we believe to have included the major uncertainties and reflected reality as much as possible. However, they only shed light on the robustness of insect BMs in a small number of scenarios. Therefore, the robustness results reflect a partial reality, as other potential uncertainties could impact BMs in different ways. We see this selectivity as a consideration for scenario analysis in general.



***Expected impact of uncertainties***

On the basis of our findings related to regulations on the use of side streams, it was observed that liberal side-stream regulations were expected to enhance their availability, leading to an anticipated reduction in prices, thereby benefitting the *cost structure* of insect BMs. These results are in line with Veldkamp et al. (2022), who concluded that inclusion of non-utilised side streams could enhance cost-effectiveness of insect production systems. In addition, experts' expectations about the increase in circularity of production by including non-certified and more low-value side streams in insect diets are also mentioned by Aiking and De Boer (2019). Despite these economic and circular possibilities for BMs under liberal side-stream regulations, all experts in our study anticipated great concerns about the assurance of safety, quality, and along the supply chain for the three BMs. Remarkably, these concerns related to the use of non-certified side streams had not been reported in previous literature. A related aspect, i.e. the lack of standardisation on the use of side streams, was mentioned by Meyer et al. (2021) and Pinotti and Ottoboni (2021). Meyer et al. (2021) further concluded that available data on the safety of side streams are fragmented, implying that additional scientific insights and sectoral regulations are needed for successful change in side-stream regulations.

With respect to insect welfare regulations, it stood out that the presence of welfare regulations would benefit BMs and that there is a need for a pro-active sectoral approach in designing and implementing these. The need for such an approach was also emphasised by Barett and Fischer (2023), who concluded that transparent interdisciplinary collaborations are essential to guide the insect industry towards feasible insect welfare regulations. However, more scientific insights are needed to establish such welfare regulations (Klobučar and Fisher, 2023).

With regard to the sustainability requirements and energy prices, it became clear that high energy prices in particular would form a major threat to insect businesses. Focus groups were held during a period of peaking energy prices, which contributed to business failures in the insect sector in some European countries. This external factor might have influenced the impact assessment of experts in our study. Compliance with sustainability requirements was generally evaluated positive as such requirements were expected to lead to more positive sustainability evaluations benefitting the selling position of insects on all considered markets. In line with Aiking and De Boer (2018) and Wade and Hoelle (2020), experts mentioned that additional scientific evidence on sustainability evaluations (e.g. a standardised and transparent approach for data collection) and strong multidisciplinary collaborations are needed for implementation of sustainability requirements.

***Use and suitability of the method***

We applied the BMST to multiple generic and potential BMs which not only provided insights on the robustness of different BM components but also revealed required actions for businesses and the entire sector in the studied scenarios. Considering that BMST has previously been applied to existing individual companies with industry experts and employees (Bouwman et al., 2018; Haaker et al., 2017), we see our use of BMST for multiple and generic BMs as an extension and most informative on a sectoral level (i.e. the insect sector). Furthermore, the inclusion of experts from different disciplines learned that their inputs complemented each other, resulting in complete discussions and well-reasoned arguments.

With respect to the suitability of the method, the formulation of scenarios introduced some challenges. We chose more elaborate scenarios compared to Haaker et al. (2017), with the aim of giving a complete picture of scenarios and to facilitate the discussion. In practice, the discussion among experts typically started with the initial (i.e., the first) part of the scenario; the consequentiality in the scenarios was confirmed by the experts during the focus groups. However, for the third uncertainty type, we included two seemingly unrelated components (i.e. sustainability requirements and energy prices). In practice, one scenario's discussion primarily evolved around high energy prices, while the other scenario's discussion focussed more on the sustainability requirements. The scenarios on sustainability requirements and energy prices have therefore not been explored to the fullest extent.

Eventually, realising that the BMST has robustness (which is a combination of technical feasibility and economic viability) as an outcome parameter, it is understandable that impact ratings have been selected and described in negative formulations. However, when considering business model innovation and development, adding a colour exclusively indicating positive impact would be beneficial. This would give more certainty in the positive impact formulations of certain scenarios. Although no ranking indicating a positive impact was present in the assessment, the focus group discussions with the underlying reasoning of experts largely revealed the distinctions between impacts seen as 'no negative impact' or possibly a 'positive impact'.



## 5.5 Conclusions and recommendations

We analysed the robustness of three European insect BMs: full-liner BSF production for pet food, decentralised BSF production for aquafeed, and mealworm processing cooperative for food, each in the context of uncertainties regarding regulations on the use of side streams, insect welfare regulations, and sustainability requirements and energy prices. We concluded that full-liner BSF production for pet food and mealworm processing cooperative for food were expected to be more robust compared to decentralised BSF production for aquafeed. The differences in robustness were primarily related to the customer segment of BM components the *customer segment*, *value proposition*, *revenue structure,* and *cost structure*. Furthermore, in general, the introduction of strict regulations for the use of side streams and for insect welfare was considered to have the least negative or even positive impact on the robustness of most BM components of pet food and food BMs (with the exception of the component of *cost structure*). The same was visible for compliance with sustainability requirements, that is, this was expected to have a less negative impact on the robustness of the BMs compared to high energy prices.

To pursue the robustness of insect businesses in general, three main areas of focus are recommended for the future. First, intra- and inter-chain collaborations should focus on obtaining data and achieving standardisations for the use of (non-certified) side streams and insect welfare practises, with the aim to jointly design feasible implementable regulations, e.g. with regard to side streams, insect welfare, and sustainability. The International Platform of Insects for Food and Feed (IPIFF) is an established non-profit organisation addressing such issues on a European level. The foundation of similar initiatives on a national level could stimulate collaboration between chain actors and governing bodies. Considering the emerging nature of the sector, we recommend policy makers to offer subsidies to finance the necessary technologies required to comply with standards. Linked to this, the design of guidance documents on operationalisation of new regulations within businesses and supply chains is suggested to successfully implement more liberal or new regulations and achieve a high compliance rate. Second, when implementing these regulations, consumer education and strong customer relationships are key to consumer trust and optimal market demand of the food, pet food and aquafeed market. The main focus should be on safeguarding product safety, quality, and transparency. Third, improving the sustainability of insect production as a result of the introduction of sustainability requirements could reveal important marketing opportunities by using sustainability evaluations (based on compliance to requirements) as competitive selling points and thus stimulate the demand for insect-based products. To implement requirements and develop evaluations this, more data on the environmental impact of different production systems should be recorded and analysed to design sustainability standards.

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**Supplementary material**

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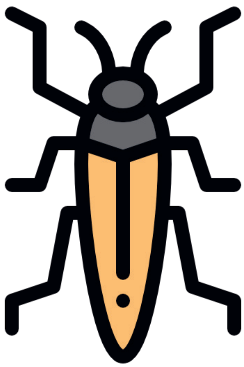

6

# General discussion

## 6.1 Background

Since its emergence in Europe, the insect sector has been characterised by the presence of many small-scale enterprises along with a few medium- and large-scale businesses. Given the versatility of insects and their potential to contribute to a more sustainable form of livestock production, higher production volumes are needed to supply the prospected demand for inclusion in feed and food formulations. However, the economic viability of insect businesses is currently unclear due to the high levels of risks and uncertainties in the dynamic insect sector. Economic viability is essential as unprofitable or high-risk operations discourage entrepreneurs from starting insect farming, banks from providing finance, and supply chain actors from investing (Hillier et al., 2016).

The overall aim of this thesis was to assess the economic viability of insect production for feed and food in Europe.

Specific research objectives (RO) were:

RO1 To review the profitability of insect production for feed and food.

RO2 To analyse the profitability of insect production in the Netherlands.

RO3 To assess past barriers, future risks, and risk management strategies in European insect supply chains.

RO4 To assess the robustness of three potential business models for insect production for feed and food in Europe.

The remainder of this chapter is structured as follows: Chapter 6.2 explains how the different components of economic viability were examined throughout the thesis, and synthesises results while relating these to existing literature. Chapter 6.3 addresses the limitations of this thesis and postulates avenues for future research. Chapter 6.4 gives an overview of relevant policy and business recommendations. The chapter closes with the main conclusions of this thesis (Chapter 6.5).

## 6.2 Synthesis of results

The Chapters 2 to 5 in this thesis addressed three main themes to better understand the economic viability of insect production for feed and food in Europe: (i) economic performance of insect production, (ii) risks and uncertainties for insect producers and downstream chain actors, and (iii) potential business models for upscaling insect production.

### *Economic performance*

The economic performance of insect production was assessed by evaluating business profitability. Chapter 2 assessed the profitability of insect production through reviewing economic data from prior studies. Due to the incipient nature of economic research in the insect sector and a consequent scarcity of economic data pertaining to investments and operational costs for insect production, the review solely included operational profitability, which was derived by deducting operational costs from revenues. This was done for three main insect types (*H. illucens*, *T. molitor*, and *A. domesticus*) used for feed and food in Europe. In Chapter 3, the profitability of existing small-scale *T. molitor* producers was empirically investigated through an inventory of investments, revenues, as well as non-allocated and variable costs. The analysis involved computing both operational and business profitability. Operational profitability represents the profit from revenues after deducting the costs directly attributable to production, and provides insights in the insect business's operational efficiency. Business profitability refers to the returns from its investments and operations, and presents understanding into its potential to generate positive returns over the long run.

In Chapter 3, it was concluded that small-scale insect production was unprofitable, unless there was a substantial share of unpaid labour, i.e. own or family labour. While the literature-based operational profitability calculations were done for three insect species (*H. illucens*, *T. molitor*, and *A. domesticus*) (Chapter 2), the empirically-based calculations focused solely on one insect species, namely *T. molitor* (Chapter 3). The findings concerning the literature-based operational profitability of *T. molitor* production (Chapter 2) significantly diverged from the empirically-based results (Chapter 3). Operational costs were higher and sales prices were lower for the empirically-based study (Chapter 3). These differences can be attributed to the additional cost components incorporated in the total operational costs in the empirical-based study (Chapter 3), and the use of sales prices for the human food and pet food market (Chapter 2) versus farm-gate prices for the pet food market (Chapter 3). What did coincide between Chapters 2 and 3 were the conclusions regarding the main cost components for production: feed and labour. The following paragraphs will elaborate on the findings related to economic performance by first addressing the revenues and then the two main cost components of feed and labour. Second, particular attention is given to the investments made for small-scale *T. molitor* production, aiming to provide a more comprehensive perspective on the profitability of insect production.

*Revenues*. Chapter 3 identified two main revenue streams for small-scale insect production: sales of fresh larvae and sales of frass, with the sales of fresh larvae covering the largest share. Chapter 2 used retail prices for different processing formats of produced insects (i.e. fresh, dried, or meal) as proxies for sales prices, which in turn reflected revenues. These sales prices were related to the geographical location and the type of the sales market, as well as the quantity sold (small or larger batches) (Chapter 2). The products with the highest sales prices were sold in the food market, followed by the pet food, and the feed market (Chapter 2). Small-scale *T. molitor* produce in the empirically-based study was primarily destined for the pet food market, but producers expected to obtain higher revenues from sales in the food market (Chapter 3). Experts confirmed that in general sales prices in the food and pet food market were higher compared to the aquafeed market (Chapter 5). Regarding sales of *H. illucens*, the pet food market currently provides the highest returns, but it is not expected to drive the demand on the longer term (Rabobank, 2021). Instead, aquafeed is expected to be the main demand driver for the *H. illucens* market in the future, but a larger production scale is needed for cost-price reduction to compete with conventional feed sources (Rabobank, 2021). Chapter 3 further revealed that price variations did not only exist across markets and geographical locations (as demonstrated in Chapters 2 and 5), but also within the same market and location for identical products.

In Chapter 3, it was found that the revenue stream sales of frass only constituted a small part of the total revenues for a minority of the small-scale *T. molitor* producers. Its commercial sales practice was not (yet) commonly adopted by most producers (Chapter 3). Hence, insect producers indicated that current legislation on commercial sales of frass as fertiliser limited their business performance (Chapter 4), as frass first needs to undergo a hygienisation process of one hour at $70^{0}$C before it can be commercially sold as fertiliser (IPIFF, 2021). Considering the relatively low volume of frass production of small-scale insect producers (Chapter 3) and the current low commercial value (Smink and Huulgaard, 2022), small-scale producers likely have to outsource this process, further reducing this revenue source.

*Feed costs.* Chapters 2 and 3 both showed that feed and labour were the two major variable cost components of insect production; this was also substantiated by Chapter 4. Feed and labour covered on average 38% and 54% of total variable costs for small-scale *T. molitor* production, respectively (Chapter 3). Chapter 3 further revealed that differences in feed costs were in part related to feed quality and frequency of feeding. While higher feed costs initially increased the cost-price (Chapter 3), higher feeding frequency and better feed quality may be positive for the growth rate of *T. molitor* and the quality of the end product, i.e. larvae (Bordiean et al., 2022; Riekkinen et al., 2022; Yang and Cooke, 2020). These positive impacts could then enable for higher pricing which enhances profitability. End product quality was in particular considered relevant for the food and pet food market (Chapter 5). It should be noted, however, that the growth and quality of the *T. molitor* larvae is not only related to feed use (as reflected by feed costs), but that many other factors such as temperature, humidity, and larval density could also affect *T. molitor's* (and other insect types) growth and quality (Pinotti and Ottoboni, 2021).

The scope of feed types that could be (and is) used for *T. molitor* production is currently smaller compared to the scope used for *H. illucens* production. *H. illucens* can grow on a large range of low-value side streams. However, many of these side streams are currently unauthorised for insect feed use (Leni et al., 2021). The results of this thesis highlighted that current legislation on the use of side streams limited the business performance of insect producers (Chapter 4). In line with Broeckx et al. (2021) and Rumpold et al. (2013), the results further showed that liberalising these regulations provided opportunities to reduce operational costs, in particular for *H. illucens* production (Chapter 5). Experts expected that with such liberal regulations feed prices would reduce due to increased side-stream availability (Chapter 5). Several feasibility studies for *H. illucens* production (see e.g. Pahmeyer et al. (2022) and Spykman et al. (2021)) posit that utilising side streams as insect feed can yield returns, as these materials are often deemed waste from the food industry. In these studies, side streams are therefore included as negative costs (Pahmeyer et al., 2022; Spykman et al., 2021). However, experts indicated during the business model assessment that including side streams as negative costs posed high risks and was not economically viable (Chapter 5). In addition, Spykman et al. (2021) showed that the efficiency of *H. illucens* production declines with the use of low-value side streams prolonging the production time, thus potentially increasing operational costs. With respect to *T. molitor* production, the possible fraction of wet feed used in the total feed was relatively low (Chapters 3 and 5) compared to the fraction in *H. illucens* feed (Chapter 5). Technical and economic feasibility studies which further evaluate opportunities to efficiently use different side streams for *H. illucens* and *T. molitor* production are essential to economically profit from liberal side-stream regulations.

*Labour costs*. The relevance of high labour costs, the second main cost component, was corroborated by insect producers (Chapter 4) and emerged even more clearly in the profitability calculations for small-scale *T. molitor* production (Chapter 3). Hence, Chapter 3 concluded that small-scale *T. molitor* production was not profitable, unless there was a substantial share of unpaid labour involved. Maroušek et al. (2023) also showed the significance of labour costs for production. These labour costs were primarily related to the labour intensiveness of operations such as the execution of the reproduction process, the frequent feeding, and the regulation of climate control (Chapter 3 - and also addressed by Dobermann et al. (2017)). Hence, mechanisation has been proposed as a relevant factor to reduce labour costs, see e.g. Cadinu et al. (2020). To showcase options for small-scale mechanised production systems, Pahmeyer et al. (2022) recently modelled a small-scale automated container production system for *H. illucens* production. The authors concluded that such a production system is only economically viable when sales prices for insects and derivatives fall within the higher value category, i.e. above the range of conventional feed prices. Even though mechanisation is expected to reduce labour costs, maintenance costs for mechanised systems and high energy costs related to mechanisation should not be overlooked in future studies comparing the feasibility of manual and mechanised production systems.

*Investments*. With respect to investments, Chapter 3 demonstrated that the economic performance of small-scale *T. molitor* production was related to the investment strategy, i.e. the choice for new or pre-owned production systems. Initiating a business with new materials and their corresponding substantial initial investments led to a less favourable net present value outcome, in contrast to starting with pre-owned materials (Chapter 3). Nonetheless, potential differences in depreciation time between new and pre-owned production systems were not considered in this study. Accounting for different depreciation periods could have reduced the net present value differences between new and pre-owned initiated businesses. Small-scale *T. molitor* producers considered in this thesis were primarily using manual production systems (Chapter 3). Mechanisation of production is suggested to decrease operational costs (Cadinu et al., 2020; Ortiz et al., 2016). Investment costs for mechanised systems are, however, considerably higher than manual systems. Pahmeyer et al. (2022) estimated the investments for a mechanised container-based system for *H. illucens* production to be as high as 271,362 EUR/kg of dried larvae. This system also includes a processing (drying) step, which increases the value and revenue of the systems' end product. Average investments for buildings and installations, as well as machinery and other assets for small-scale *T. molitor* production were 4,196 EUR and 2,773 EUR/tonne of produce, respectively (Chapter 3). These investments were for the primarily manual production of fresh unprocessed larvae. The feasibility of suggested mechanised system in Pahmeyer et al. (2022) depends on optimal sales conditions, as substantial investments necessitate robust market demand and favourable selling prices. Groeneveld et al. (2023) recently examined the economic feasibility of small-scale mechanised production utilising partially horticultural side streams as feed, which were considered negative costs. Their findings indicated that this was not economically viable for small-scale production systems. Large-scale production under similar conditions was only considered economically viable with favourable sales prices, aligning with the conclusions drawn in the study by Pahmeyer et al. (2022). Concurrently, the availability of different techniques for mechanised insect production is still limited (Van Peer et al., 2022) which constraints insect producers in upscaling and achieving high economic performance (Chapter 4). Addressing mentioned challenges on marketing and sales together with improving access to mechanisation technologies are essential steps to fully capitalise on the potential benefits of mechanised production methods in the insect industry.



### *Risks and uncertainties*

Agricultural businesses are exposed to high risks and uncertainties impacting their economic viability (Lezoche et al., 2020).

The primary risks associated with agricultural production are typically classified into five overarching categories: production, price and market, institutional, human, and financial risks (Hardaker et al., 2015). In the context of this thesis, a specific focus was placed on assessing risks within four stages of the supply chain: rearing, processing, insect-based feed production, and insect-based food production. Chapter 4 of this thesis involved the identification of the most relevant risks within the insect sector, which were then categorised into four risk domains: (1) operational; (2) financial, cost, and market; (3) worker and food safety; and (4) regulatory risks. These domains were thus derived from the former categories outlined by Hardaker et al. (2015). Risks were assessed based on both their perceived probability and negative impact on business performance (Hardaker et al., 2015; Teece et al., 2016). The six most important risks and uncertainties for businesses in the insect supply chain and the dynamics of these, as demonstrated in this thesis (Chapters 4 and 5), are discussed hereafter. These risks were: (1) the quantity and quality of supplied insects for insect-based feed producers, (2) limited access to finance for insect producers, (3) insufficient market demand for insect-based food producers, (4) low output and high input prices across chain stages, (5) the potential food safety risks of insect-based feed and food products, and (6) restrictions for insect-based food producers.

*Quantity and quality of supplied insects for insect-based feed producers.* The main operational risks for insect-based feed producers related to the incoming supply (i.e. insects). The options for incorporating insects in feed formulations were, amongst other factors, limited by the insufficient production volumes of insects (Chapter 4). The findings corroborated Albrektsen et al. (2022) and Gasco et al. (2023), who observed that the existing production quantities fall short of the projected volumes demanded by the aquafeed industry, which is predicted to emerge as the largest market for insect-based feed in the future (Rabobank, 2021). Together with sufficient quantities, adequate and consistent quality of insects were deemed necessary for insect-based feed producers to ensure reliable and stable quantity and quality of produced insect-based feed formulations (Chapter 4). In addition, Alfiko et al. (2022) and Thrastardottir et al. (2021) indicated that a year-round availability, a consistent quality, and a high nutritional value of insect-based feed formulations are necessary for competition with conventional feed proteins. Furthermore, Roos et al. (2023) emphasised the need to establish quality measures throughout the chain to ensure consistency. This thesis showed that consistency of quality and quantity is a priority for business operators throughout the chain. This priority was illustrated by the main applied risk management strategies focusing on investments in techniques to guarantee a stable quantity, quality, and hygiene of production (Chapter 4). Insect-based feed producers foresaw a rise in risks regarding future developments concerning supplied insects, as well as operational risks in general. Specifically, they were concerned about restrictive regulations (Chapter 4). Changes in regulations can alter the (relative) importance of risks. Experts expected for instance that the introduction of liberal side-stream regulations, requiring a change in legislation, would increase side-stream availability and stimulate the expansion of insect production volumes (Chapter 5). However, implementation of these liberal side-stream regulations was also expected to increase quality risks of side-streams, insects, and their derivatives (Chapter 5). Liberal regulations on the use of side streams were thus expected to mitigate risks related to insufficient production volumes, but were simultaneously expected to increase quality risks. Experts considered these quality risks to be important for all markets, but slightly more for the food and pet food than for the aquafeed market (Chapter 5). Alfiko et al. (2022) also stressed the importance of quality and safety of insect-fed aquafeed when using low-value side streams.

*Limited access to finance for insect producers.* Insect producers expected that a limited access to finance from banks would impede the transition towards (large-scale) mechanised production aimed at cost-price reduction through lower labour requirements and economies of scale (Ślusarczyk and Grondys, 2019). Insect producers primarily sought to mitigate this financing risk by seeking financial support from alternate sources, for instance through external loans or external funds. Thrastardottir et al. (2021) also mentioned that many insect businesses rely on private or venture capital, and external funding. Even though the importance of this financing risk was recognised, producers had an optimistic outlook on future financing prospects. Regarding investment risks, stakeholders perceived the potential decrease of current asset value due to rapid technological innovations as relatively minor for business performance (Chapter 4). Moreover, experts highlighted that changes in legislation often necessitate the adoption of new or additional techniques (Chapter 5), which could introduce another source of uncertainty into investment decisions. The relatively lower emphasis placed on depreciation risk by insect producers might be attributed to the dominance of small-scale insect producers in the sample (and sector), who did not yet invest in high-capital mechanised production.

*Insufficient market demand for insect-based food producers.* Insect-based food producers expected market related risks, which encompassed insufficient and fluctuating demands for insect-based food products (Chapter 4). The insufficient market demand is, among other factors, linked to the low social and consumer acceptance of insect-based food products (Alhujaili et al., 2023). Notably, insect-based producers indicated that the understanding of how to effectively incorporate insects into food formulations was growing, potentially enhancing the overall acceptance among consumers (Chapter 4). To further stimulate the acceptance of and demand for insect-based food products, actors throughout the chain mentioned to participate in education activities as a way to increase human exposure to insects (Chapter 4). Exposure to insect-based food products (Alhujaili et al., 2023) and incorporation of insects in familiar food products (Roos et al., 2023) are described as relevant strategies for insect-based food producers to increase consumer acceptance. Marquis et al. (2020) further underscored that the involvement of a marketing council or board would be essential to achieve faster and more substantial impact. Nevertheless, a cautious approach was advised in the development and promotion of insect-based food products (Chapter 5). This caution was particularly considered necessary due to sensitive consumer concerns about aspects like food quality, safety, and transparency (Chapter 5). Despite not expecting consumer acceptance to improve in the near future, insect-based food producers displayed optimism regarding the developments in market demand (Chapter 4).

*Low output and high input prices for actors across the supply chain.* Business operators across the insect supply chain encountered price risks (Chapter 4). For insect producers these risks considered low output prices for produced insects. These prices were concurrently regarded as high input prices for insect-based feed producers (Chapter 4). For insect-based feed producers it would, therefore, no longer be profitable to incorporate insects in their formulations (Chapter 4 and also demonstrated in Sogari et al. (2023)) as their formulations need to compete against soy and fishmeal (Rabobank, 2021). Consequently, the pet food and food market are presently considered the two most accessible high-end target markets for insect business operators (Chapter 5 and also mentioned in Rabobank, 2021). Regarding future developments, insect producers expected increasing risks associated with low output prices, but insect-based feed producers expressed a neutral opinion on input prices (Chapter 4).

*Potential food safety risks of insect-based feed and food products.* In contrast to regulatory risks, worker and food safety risks were generally not considered of major importance for insect business operators throughout the supply chain (Chapter 4). Nevertheless, experts expected that regulatory changes on, for instance, the ability to use certain side streams as substrates might elevate food safety risks in insect supply chains (Chapter 5). The side streams currently permitted as feed for insects are limited to feed ingredients authorised for farmed animals, including materials from vegetal origin, and milk and eggs (IPIFF, n.d.a.). The utilisation of existing side streams was considered as constraining and a potential risk factor for business performance of insect producers (Chapter 4). Liberalising regulations has been suggested to increase availability of substrates and reduce feed costs for insect production (Broeckx et al., 2021). The projected economic benefits from liberalising side-stream regulations were, however, expected to (partly) diminish due to risks related to variations in the quality of produced insects and processed end products by using low-value side streams (Chapter 5). Furthermore, it was expected that food safety risks related to feed and food formulations would increase due to these changes. These food safety and quality risks were projected to cause large consumer concerns and negatively impact sales (Chapter 5). Hence, strict side-stream regulations were expected to benefit consumer trust and sales (Chapter 5). On this matter, Bruschi et al. (2015) mentioned that by collectively striving for stringent regulations and efficient enforcement, it is possible to achieve enhanced consumer trust in emerging markets. Overall, consumer trust was considered vital to stimulate market demand for insect-based feed and food products (Chapter 5) and strict regulations appeared to benefit insect businesses (Chapter 5).

*Regulatory restrictions for insect-based food producers.* Insect-based food producers primarily faced regulatory risks arising from national restrictions that limited the incorporation of insects in food (Chapter 4). Additionally, they faced risks around the administrative and costly authorisation processes at the EU level, partly due to the scarcity of safety data required for obtaining such authorisations (Chapter 4). Insect-based food products need to be authorised under the Novel Food Law, prior to their lawful marketing (IPIFF, n.d.b.). Given the five year data protection possibility with Novel Food dossiers, the larger businesses benefit from market exclusivity in the first five years after approval of an application (IPIFF, n.d.b.). These constraining regulations on incorporation of insects in food products further hamper the previously described consumers' exposure to insect-based food products, and further impede the stimulation of consumer demand (Nguyen et al., 2022). In general, stakeholders from all supply chain stages, except insect-based food producers, anticipated an increase in regulatory risks (Chapter 4). Regulatory changes were anticipated to have large implications for insect businesses throughout the supply chain (Chapter 5). To mitigate risks, insect business operators made efforts to lobby with regulatory bodies on local and higher levels (Chapter 4). Experts further advocated for a joint design and feasible implementation scheme of new or modified regulations (Chapter 5).

***Business models***

The protein transition and the circular economy have emerged as two intertwined approaches offering potential solutions in response to growing environmental concerns, resource depletion, and increasing nutritional demands (Aiking and De Boer, 2020). Successful implementation of these approaches depends on viable business models at different scales (Paloviita, 2021). It is particularly essential that these business models foster (cost)-efficient production, sustainable sourcing, market access, and consumer acceptance (Aiking and De Boer, 2020; Ciulli et al., 2022; Geissdoerfer et al., 2020; Lweandowski, 2016). The production of insects for feed and food is generally regarded as a sustainable and circular solution in the context of the protein transition (Henchion et al., 2017; Van Huis and Oonincx et al., 2017). However, the integration of the protein transition and circular economy approaches in business models for insect production does not (yet) fully achieve its intended goals. When considering the contribution of the insect sector to the protein transition, the key focus lies in scaling up production volumes and integration of alternative protein sources into mainstream animal diets and human eating patterns (Paloviita, 2021). The progress in contributing to the protein transition is limited hitherto, mainly due to regulatory restrictions and a low level of consumer acceptance (Van der Weele et al., 2019). In relation to the enhancing the circularity of insect production systems, the emphasis is on resource efficiency, nutrient cycling, and waste reduction (Derler et al., 2021). Furthermore, adopting a local approach to reduce transport-related emissions can contribute to more circular production systems (Derler et al., 2021). Complete circularity in insect production systems is yet to be realised, mainly due to the competition between current input streams for insect production and those required for conventional livestock and food production (Lalander and Vinnerås, 2022; Parodi et al., 2022).

Economic sustainability is integrated in sustainable and circular systems; it entails fostering economic viability while also addressing environmental and social considerations to achieve lasting balance and resilience (Slijper et al., 2020). To address the economic viability of business models for insect production, this thesis examined four different business models, two for *T. molitor* and two for *H. illucens* production. The business models for *T. molitor* included a small-scale standalone production and a processing cooperative for food. The business models for *H. illucens* included a full-liner production for pet food and a decentralised production for aquafeed. The following section first reflects on the small-scale standalone *T. molitor* production and second on the added value of a cooperative for small-scale *T. molitor* production. After that, it discusses the increasing scale of production and presents two potential business models for upscaling *H. illucens* production. After an elaboration on the challenges for upscaling insect production, the section closes by discussing the increasing scale of production as a solution for insect production in the light of the transition towards more circular livestock systems and the protein transition.

*Small-scale standalone T. molitor production*. Small-scale *T. molitor* producers examined in this thesis controlled all operational processes for reproduction, rearing, harvesting, and sales by themselves (Chapter 3). These operations each required specific expertise and presented considerable challenges for producers who operated within highly dynamic business environments (Chapter 3). Results showed that on average 80% of total labour hours for small-scale *T. molitor* production represented the direct care of larvae for reproduction and production (Chapter 3). The remaining labour hours were allocated to additional activities including administration, marketing, and transportation (Chapter 3). The sales process was regarded as laborious and time consuming inter alia due to the absence of buyer contracts. Furthermore, producers with relatively limited experience in the market encountered challenges in selling their produce at a profitable margin (Chapter 3). The sales process was conducted on a weekly basis and larvae had to be sold within a limited time after harvesting, due to the absence of a processing step (Chapter 3).

*The added value of a cooperative for small-scale T. molitor production.* The absence of a processing step presents a significant challenge for storing products and managing the supply and demand (Melgar-Lalanne et al., 2019). In Chapter 5, therefore, the possibility of a *T. molitor* processing cooperative was examined. In this cooperative, producers independently managed the production process, but collaboratively engaged in the processing step. The processing cooperative, with insect producers as its members, functioned both as a first stage processing facility and a subsequent sales handler (Chapter 5). Implementing a processing step would enable the cooperative to build up stock and enhance its responsiveness to fluctuations in supply and demand (Chapter 5). Furthermore, joint processing would result in larger supply volumes, which, in turn, could grant the cooperative members greater bargaining power to secure more profitable sales prices (Chapters 3 and 5, and also mentioned by Bijman (2018)). Moreover, maintaining consistent supply volumes would allow for entering contracts with buyers (Bijman, 2018). In addition, joint frass hygienisation could increase opportunities to sell larger volumes of frass as fertiliser at a commercial level (Chapter 5). Critical aspects in initiating the described processing cooperative encompassed high-level cooperative management, optimal logistics structure, good cooperation between members, and strict agreements on handling and quality requirements of delivered insects to be processed (Chapter 5, and also mentioned by Chaddad (2012) and Velychko (2015)). The suggested processing cooperative thus presents an opportunity to maintain small-scale entrepreneurship within the insect sector while increasing the economic viability of small-scale insect producers.

*Increasing scale of production.* The adoption of large-scale mechanised insect production has been proposed to minimise labour costs, to achieve economies of scale lowering the overall cost-price, and to meet the prospected growing demand from the feed market in particular (Veldkamp et al., 2022). In the past decades, other European livestock sectors have gone through a process of upscaling to enhance productivity and improve cost-prices through economies of scale, leading to enhanced (international) market competitiveness (Fresco and Poppe, 2016). Nevertheless, this upscaling process also brought forth various challenges concerning environmental sustainability (e.g. resource utilisation and emissions), land availability, and socio-economic conditions (Opio et al., 2012). Balancing economic development, environmental impact, and societal factors becomes vital for sustainable and resilient upscaling of livestock sectors (Knickel et al., 2018; Meuwissen et al., 2019). This calls for more innovative and collaborative approaches (Fritsche et al., 2020; Meuwissen et al., 2022).

*Two potential business models for upscaling H. illucens production.* Considering the aforementioned positive sustainability aspects of insect production, this thesis further evaluated two business models which have a potential for upscaling *H. illucens* production; a central and a decentralised model (Chapter 5). In the central business model, all operational processes, from the reproduction until the processing of a marketable product, were consolidated at a single location (Chapter 5). In the decentralised business model, reproduction and processing were carried out on one location, but the production was dispersed across smaller facilities (Chapter 5). The central business model offered advantages over the decentralised model in terms of transport time and handling, as there was no transportation of commodities between the production and processing steps (Chapter 5), reducing the risks associated with logistics between sites. The decentralised model, with its dispersed production locations, allowed for sourcing side streams in close proximity to these facilities, potentially enhancing circularity of production (Chapter 5). These transportation aspects were not investigated quantitatively in this thesis. The business models examined in this thesis were considered to produce for a single target market; the central business model produced for the pet food market, while the decentralised business model produced for the aquafeed market. Both business models offered opportunities to capitalise on economies of scale, increase profit margins, and reinforce economic viability. The cost-efficient upscaling of insect production could contribute to driving the participation of insect production in the protein transition.

*Challenges related to upscaling insect production.* Similar to other livestock production sectors, upscaling of the insect sector comes with challenges. A first challenge faced by the insect sector encompassed the limited market demand for insect-based products (Chapter 4). Increasing this demand remains difficult. Insect-based feed and food products need to compete with conventional protein products, which are already widely embedded in animal and human diets (Van der Weele et al., 2019). Second, despite its positive sustainability aspects, the energy-intensive nature of insect production raises sustainability concerns, calling for solutions such as renewable energy sources and innovative large-scale production systems (Chapter 5 and also shown in Smetana et al., 2021). Third, the competition for feed sources with conventional livestock remains a debate (Thornton et al., 2023). The successful incorporation of emerging agricultural sectors hinges on economic viability, environmental considerations, and scalability potential. Even though, this is needed to ensure the viability, sustainability, and resilience of emerging sectors, it also brings about heightened integration obstacles for entrepreneurs in these sectors (Gatto and Re, 2021). These challenges were further considered to be magnified by the limited availability of data concerning for instance economic feasibility and environmental impacts of emerging sectors (Chapter 5). In addition, the transition from the current focus on the pet food market to the human food and animal feed market necessitates addressing other previously described challenges, such as high production costs and consumer concerns (Chapter 5).

*Increasing scale of production as a solution for insect production.* Currently, the majority of *T. molitor* and *H. illucens* production is directed towards the pet food market due to the favourable sales prices in this market. However, *T. molitor* might not be the optimal choice for inclusion in feed formulations given its higher production costs (Tavares et al., 2022). Conversely, *H. illucens* has the advantage of being cultivated on lower-value side streams, making it a more viable option for cost-effective feed production compared to *T. molitor*. A strategic approach would, therefore, involve prioritising *T. molitor* production for the human food market to maximise profits while ensuring a steady offtake from the pet food market when demand from the food market is suboptimal. Simultaneously, *H. illucens* production could be expanded in response to the present and anticipated rise in pet food demand, capitalising on economies of scale to eventually penetrate the (aqua)feed market through cost reduction and enhanced production volumes. Overall, upscaling insect production can thus be realised through the co-existence of different business models, in which the cooperative model has more potential contribute to the local production aspect of the circular economy, while the central and decentralised models aim to cost-efficiently produce large volumes to supply larger markets. It is noteworthy that the successful implementation of these diverse business models hinges on the adept resolution of challenges, as deliberated upon in this section including the current limited market demand and energy-intensive nature of large-scale mechanised production.

## 6.3 Research limitations and further research

### *Research limitations*

*Sample.* The emerging nature of the insect sector posed challenges for data collection, as the sector is characterised by a low number of businesses resulting in limited sample sizes in the conducted studies. In particular, the sample size for the small-scale *T. molitor* producer interviews was relatively small (Chapter 3). The business economic data obtained from producers could have been enriched by gathering additional data points (including optimum, least, and most likely values) for a range of variables, such as production volumes and sales prices (Chapter 3). Such an approach would have enabled the integration of uncertainty and variability in the outcomes, thereby providing a more realistic representation, as done by e.g. Gebrezgabher et al. (2012) for the economic feasibility of manure digestion. Furthermore, supplementing the data collection with inputs from experts could have also provided more data and enhance the validity of results (Ngoc et al., 2016). In addition to the data collected, the exclusivity of business economic results for small-scale production (Chapter 3) hindered a comprehensive understanding of the economic performance of the entire sector including also medium- and large-scale producers. Incorporating results from these producers could have provided a more complete and nuanced perspective of the insect industry. Despite these limitations, the obtained results are considered to provide a realistic representation of the present state within the European sector, as the sector is dominated by small-scale producers (Thrastardottir et al., 2021). Results namely provide tangible and evidence-based insights into the business economics of small-scale insect producers. These realities and empirical data can serve policy makers and other stakeholders to make informed decisions and design effective strategies addressing practical necessities and focus on the actual needs and requirements in the field. While business economic results were not obtained from large-scale producers (Chapter 3), efforts were made to involve large-scale producers and other stakeholders in the studies on perceived risks (Chapter 4) and business models (Chapter 5). By utilising empirically obtained data to assess perceived risks (Chapter 4), study results provided insights into the (economic) viability of both small- and large-scale businesses. This enabled the identification of focal areas for economic viability of each actor in the chain. Additionally, assessment of specific business models (Chapter 5), resulted in a more concrete understanding of the qualitative aspects governing the economic viability of small- and large-scale insect production in Europe.

*Study participants.* Throughout this thesis, empirical data were primarily collected from producers, stakeholders, researchers, and consultants with expertise of the insect sector. In addition, the risk survey was extended to (non-insect-based) feed producers to gain insights into the broader perception of the feed industry of future risks for incorporating insects in their formulations (Chapter 4). The inclusion of feed or food producers was limitedly the case for the business model assessments (Chapter 5). The involvement of more established feed and food producers could have contributed to more comprehensive and multifaceted outcomes. In addition, engaging banks and financiers through interviews could have provided valuable insights into their risk perceptions on the sector, which could be compared to those from industrial stakeholders (Chapter 4). These comparisons could then enhance understanding between various stakeholders, potentially also leading to more productive collaborations. With respect to the distribution of participants across different geographic locations, the data were primarily collected from stakeholders in the northwestern and partially southern regions of Europe. Although a number of participants from eastern Europe were involved in the risk survey (Chapter 4), an underrepresentation of results from this region is observed. The underrepresentation is (in part) related to the relatively lower presence of insect businesses in this region. While their inclusion in the empirically based studies (Chapters 3-5) could have provided a more comprehensive Europe-wide perspective, it would have posed significant challenges in data collection and analysis. In addition, it is recommended to conduct data collection and analysis for business economics, risk assessment, and business models tailored to each region. This regional approach will yield more accurate guidance at both the national and European levels, enabling a deeper understanding of the economic viability of the insect industry and of the market potential in each part of Europe.

*Limited quantitative results.* The main limitation in results obtained in Chapters 4 and 5 originates from the absence of quantitative outcomes. In Chapter 4, the perceived probability and impact of identified risks were assessed via a Likert-scale, a semi-quantitative measurement. Quantification of absolute impacts of risks on business profitability would have enriched results and enhanced their usability for credit providers and other parties. Although the impact of risks (Chapter 4) was not quantified in absolute terms, the analyses and results offered an indication of the priorities for the sector, based on their relative importance. Furthermore, the absence of quantitative impacts also emerged during the investigation of robustness of business models for insect production (Chapter 5). The exploration of business models and the qualitative assessment of their robustness are regarded as a fundament offering policymakers and businesses information, as well as guidance for interventions and decision-making. Nevertheless, to obtain a well-established view on economic viability, a more quantitative approach to business models is essential. Quantitative data for small- and large-scale business models on for instance logistics, market volume, operational costs for mechanised production, as well as the more detailed showcasing of end products to specify the value proposition (as compared to competitors) would enrich such studies. With these data, empirically based viability studies would exhibit more concrete and reliable business cases. Implementation of viable business cases could then further contribute to actual sector development.

*The dynamics in the sector during the data collection processes.* The dynamics of the insect sector in terms of developments, emergence, and company fluctuations in the time span between the start (October 2020) and final data collection points (March 2023) of the studies in this thesis have potentially influenced the consistency of results across the different chapters. In particular in the years 2021 and 2022, the insect sector has experienced regulatory changes, such as the authorisation of certain insect-based feed and food products, as well as political and logistic developments that led to significant spikes in feed, energy, and gas prices. While these developments did not yield observed differences in results within individual studies, they could have contributed to variations between studies. The regulatory changes may have depicted a more positive outlook, while the rapid increase in production costs could have adversely affected the economic viability of insect production.

***Recommendations for further research***

This thesis lays the foundation for understanding the economic viability of insect production for feed and food in Europe. To gain a more comprehensive understanding on this topic, it is essential to conduct further (quantitative) research examining economic viability of insect production and processing for different production scales, chain-set ups, and market sizes. The findings from such research will enable stakeholders to make better informed decisions, exploit the true potential of insect production, and foster sustainable sector growth.

To gain a comprehensive understanding of economic performance of insect production for feed and food in Europe, more detailed quantitative business data of insect production at different scales, of different business models, and across various regions are needed. Such research involves data collection of sensitive information. Ensuring participants' data confidentiality and exclusively publishing aggregated results are crucial aspects in enhancing participants' willingness to engage in such studies. The involvement of large-scale businesses proved highly challenging in the analyses conducted for this thesis. A potential initial step to engage these companies in such research is a European-wide approach to data collection to ensure a sufficient sample size.

With respect to research design, the technical and economic data of insect businesses should be further specified and quantified per production and processing step. Through analyses of these data, insights into the efficiency of different steps within the production and processing process will be obtained. Such detailed data will then serve to construct reliable business models and risk assessments for (starting) producers, financial institutions, and governments. If these reliable business cases and established risk profiles are not present, the configuration of a good business plan will be difficult for entrepreneurs, and credit provision will remain highly risky for banks. Eventually, these quantitative data also serve other (more technical) research areas, such as the identification of key areas for technological and/or genetic interventions which could enhance production efficiency. Even though I consider this not as the first priority for the sector, such technical or genetic interventions could contribute to achieving greater competitiveness in the feed and food market.

To enhance circularity within the insect industry and strategically plan the upscaling of the sector, it is crucial to explore different viable business models and the integration of both small- and large-scale businesses in the European insect sector. Such business models should not only focus on the economic viability, but also evaluate key sustainability aspects such as resource utilisation, waste management, and environmental impact. These aspects are increasingly gaining significance, and quantitatively identifying the sector's potential to capitalise on circularity will benefit the sector.

## 6.4 Policy and business recommendations

The findings of this thesis have implications for policy makers and businesses in the insect sector. In the following sections, recommendations for policy makers, insect producers, other supply chain actors, and third parties are presented.

***Business recommendations***

*Development of low-cost small-scale technologies.* To improve the economic viability of small-scale insect production, it is essential to reduce operational costs (Chapter 3). Currently, most small-scale systems heavily rely on manual labour (Van Peer et al., 2022). A crucial step towards achieving economic viability of small-scale insect producers could include the introduction and adoption of low-cost small-scale technologies aimed at minimising labour requirements. Implementation of such technologies was also expected to enhance consistency of quantity and quality of production (Chapter 4). These technologies can be implemented in both standalone small-scale and cooperative business models. By developing and incorporating these innovations, small-scale production systems can make substantial progress towards achieving economic viability. This might be achieved in partnerships with the government.

*Collaboration.* Throughout this thesis, the significance of collaboration for the insect sector's development became evident. Chain collaborations are essential to strengthen the market position of small-scale producers (Chapter 3). These collaborations among insect producers could include exchange of information, but also the joint purchase or sales of goods. Collaborative efforts for insect-based food producers should particularly target the joint application for approval of insect-based food products at EU level (Chapter 4). Despite some stakeholders expressing interest in collaborating with both horizontal and vertical actors in the supply chain, such collaborations were found to be limited (Chapter 4). Collaboration was not only considered vital within the chain but also with external parties to establish new standards or regulations for the sector (Chapter 5). Collaboration should thus form an important pillar in the business models of the insect sector.

*Transparency.* Transparency towards customers and consumers regarding both products and operational practices was considered highly relevant for insect business operators (Chapter 5). This holds in particular for the human food and pet food markets, given their susceptibility to concerns regarding safety and quality variations (Chapter 5). Furthermore, business operators should inform increasingly conscientious consumers about welfare and sustainable practices within the production process, thereby cultivating a sense of trust (Chapter 5). Macready et al. (2020) also elaborated on the importance of operators' openness and trustworthiness for consumer trust. Gaining consumer trust was considered highly relevant in penetrating markets but also in thriving the demand for insect-based products.



***Policy recommendations***

*Development of small-scale mechanised systems.* In order to enhance economic viability of small-scale insect production through labour cost reduction, policy makers should support the development of small-scale mechanised systems at the national and local level. This entails investigations into technical implementation and economic viability of small-scale mechanised systems. Small-scale insect production, either as standalone businesses, in the form of a cooperative, or as a farm-integrated business presents an opportunity to contribute to more local and circular agricultural production systems (Liaros, 2021). The advantages of such local insect production systems lie in the utilisation of low-value side streams, conversion of these into high-value products, local feed or food provision, and the application of frass as organic fertiliser for proximate arable farms (Mancini et al., 2022; Moruzzo et al., 2021; Ojha et al., 2020). To achieve the circularity potential within these systems related to frass specifically, policymakers should further direct funding and efforts towards studying the application and commercial valuation of insect frass (Torgerson et al., 2021). Additionally, there is a need to investigate the production implications associated with the utilisation of different types of side streams. Side-stream variety could expand, especially when integrating the use of more local sources within small-scale production systems. Furthermore, a transition towards renewable energy use would enhance the environmental sustainability of small-scale mechanised systems. In light of all the aforementioned, it is recommended to translate the insights into practical business cases and actively collaborate with stakeholders on their joint implementation. Such collaboration stimulates learning and could enhance business robustness (Slijper et al., 2022).

*Feasibility studies for large-scale production systems.* In addition to developing small-scale businesses (previous point), policy should also stimulate research and development on the economic feasibility and environmental sustainability of large-scale production systems. Large-scale production systems are in particular relevant to lower cost-prices and to meet the large demands from the feed market. Specifically, the technical implementation and economic viability of such systems should be investigated. The business models proposed in this thesis, as well as results such as summarised by Saatkamp et al. (2022) and Smetana et al. (2021), can serve as a foundation. It is further relevant to identify risks specific to large-scale production systems for insect-based feed production. This could increase the chance for business success which may also reduce the risk for policy makers and investors related to subsidising of and investing in large-scale production systems. Considering that insufficient volumes are currently the largest risk for feed producers to incorporate insects into their formulations (Chapter 4), attention should be paid to increasing production volumes.

*Design and implementation of regulations.* Policy makers on national and European level are recommended to develop and implement insect welfare regulations (see also Gasco et al., 2020). The results of this thesis showed that development of insect welfare legislation was expected to reduce consumer concerns. When developing these and other regulations, it is crucial for policy makers to actively collaborate with industry experts.

Through collaboration, policymakers can design regulations that not only achieve their intended goals but also ensure operational feasibility for a successful implementation at business level (Chapter 5). Along with the design and implementation of regulations, priority should be given to the establishment of complementary industry standards. These standards should be formulated for sector-specific research procedures, production methods, processing protocols, marketable product criteria, and regulations for the final sale of products (Van Peer et al., 2022). With regard to insect-based food regulations, there is a need, especially among (small-scale) insect-based food producers, to facilitate the application process for authorisation of insect-based food products on EU-level. Small-scale business operators, in particular, faced financial constraints that hindered their ability to invest in such applications, placing them at a significant disadvantage when competing with larger companies (Chapter 4). To support small-scale insect-based food producers, policy makers could for instance provide loans for operators directly or fund collaborative research projects involving businesses to set-up joint applications for insect-based food authorisations.

*Enhancing consumer acceptance.* Governmental agencies are recommended to foster enhanced consumer acceptance through education, for instance in the form of advertisements, and by creating opportunities to expose consumers to insect products. Policy makers are further recommended to prioritise funding for research and development activities aimed at identifying and developing insect-based food products appreciated by consumers (Roos et al., 2023). Furthermore, research on effective ways to convey educational messages to consumers should be supported (Kumar et al., 2022). The findings of this thesis underline the relevance of consumer acceptance and market demand for development of the insect for food sector, making the lack of it a critical risk necessary to address (Chapter 4). While companies play a significant role in this as well, larger and more impactful results can be achieved by large-scale initiatives from governments or other relevant agencies (Marquis et al., 2020).

## 6.5 Main conclusions of this thesis

The main conclusions of this thesis are:

1. Key operational costs of insect production for feed and food in Europe included feed and labour costs (Chapter 2).
2. Sales prices of insects were related to the geographical market location, market type (feed or food), and volume of products sold (Chapter 2).
3. Small-scale *T. molitor* production in the Netherlands was considered not profitable, unless a large share of own (unpaid) labour was employed (Chapter 3).
4. Small-scale *T. molitor* production in the Netherlands presented large heterogeneity for nearly all profitability indicators (Chapter 3).

5. Across the insect supply chain in Europe important perceived "financial, cost, and market" risks encompassed difficulties to obtain finance, and pricing and demand uncertainties, while important perceived “regulatory” risks were related to restrictions on used inputs and marketed outputs (Chapter 4).
6. Regarding the dynamics of perceived risks, stakeholders expected a reduction in business risks, particularly concerning "operational" and "financial, cost, and market" risks, while perceived "regulatory" risks were expected to increase across nearly all supply chain stages of the European insect supply chain (Chapter 4).
7. The business models full-liner *H. illucens* production for pet food and *T. molitor* processing cooperative for food were considered more robust compared to decentralised *H. illucens* production for aquafeed due to differences in customer segments, value proposition, revenue structure, and cost structure (Chapter 5).
8. In general, the implementation of strict regulations on the use of side streams and insect welfare were perceived more positive for the robustness of business models, as compared to liberal or absence of regulations (Chapter 5).
9. Reducing the risks from insufficient market demand and consumer acceptance of insect-based food products were expected to become more challenging when incorporating low-value side streams due to increasing risks related to safety and quality variations (Chapters 2-5).
10. The acquisition of further data concerning side-stream availability, safety measures, economic viability, and environmental implications of small- and large-scale production systems is imperative for positioning insect production within feed and food markets and enabling effective competition with other industries (Chapters 2-5).

## 6.6 References


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# 7

# Summary

# Summary

The production of insects as a sustainable source of feed and food in Europe presents promising business opportunities, but challenges persist due to the dynamic nature of the industry. Small-scale insect businesses face challenges with profitability. Upscaling businesses requires significant capital investment, but banks and investors are hesitant due to the sector's novelty and uncertain future consumer demands, hindering the development and expansion of the insect sector. This calls for insights on the economic performance and viability of insect businesses evolving in uncertain business environments.

The general objective of this thesis was to assess the economic viability of insect production for feed and food in Europe. Three concepts were applied, being the investigation of: (i) economic performance of production by analysing literature and empirically based economic data; (ii) risks and uncertainties by assessing risk perception of actors across the European insect supply chain; and (iii) robustness of business models through an assessment of three potential models. The collection of empirical business economic data was essential in understanding the profitability of insect production and gaining insights into the main cost components for production. The evaluation of perceived risks contributed to establishing a comprehensive risk profile for all actors along the insect supply chain. Insights into robustness were essential for identifying economically viable business models. Together, these three concepts contributed to a better understanding of the current and future economic viability of insect business models.

Chapter 2 provided a comprehensive review on the operational profitability of insect production and its underlying economic figures. This review included results from peer-reviewed articles and other literature on production costs and sales prices for production of *H. illucens* (black soldier fly), *T. molitor* (yellow mealworm), *A. diaperinus* (lesser mealworm), and *A. domesticus* (house cricket). It further included a description of the European insect sector and its operational practices. In general, the availability of economic data was limited, and published data did primarily not focus on business economics. Instead, the documented data were mostly studied in the context of other research areas. Margin ranges, based on sales prices and average operational costs, were computed for three insect species. These margins included: (1) the energy, feed, and labour margin of -798 EUR to 15,576 EUR/tonne of dried *H. illucens* larvae production; (2) the feed and labour margin of 7,620 EUR to 13,770 EUR/tonne of fresh *T. molitor* larvae production; and (3) the feed margin of 12,268 EUR to 78,676 EUR/tonne of *A. domesticus* meal. Reliable margins for the production of *A. diaperinus* could not be calculated due to a lack of economic figures on operational costs. The wide range of margins could be attributed to significant variations in sales prices, primarily influenced

by geographical location, market type, and sold quantity. It is important to note that margins cannot be directly compared between insect types due to distinct cost components and diverse processing methods involved.

Chapter 3 assessed the profitability of *T. molitor* producers in the Netherlands using empirical data. Technical and economic business data were obtained during interviews with seven small-scale *T. molitor* producers from the Netherlands through extended data-collection sheets. Using the collected data on investments, non-allocated and variable costs, the gross margin and net present value were calculated as key indicators to assess profitability. To account for the high share of unpaid labour, the profitability indicators were computed with and without accounting for own labour. The resulting average gross margin and net present value after deducting "costs" for own labour of the studied producers were 1,185 EUR and -641 EUR/tonne of production, respectively. The profitability of *T. molitor* businesses was mainly related to the sales price of larvae, and labour and feed expenses. Results further showed that nearly all indicators for profitability largely differed between producers. Specifically, the wide spreads in variable expenses were likely related to the emerging nature of the small sector. In addition, the substantial variations in invested capital resulted from different investment approaches among producers.

Chapter 4 studied the stakeholders' perceived importance of past barriers, future risks, and applied risk management strategies for businesses operating in the European insect supply chain. Barriers and risks encompassed the following domains: (1) operations, (2) financial, cost, and market, (3) worker and food safety, and (4) regulations. These were assessed through an online survey with insect rearers (producers), processors, and insect-based feed and food producers. Across supply chain stages "financial, cost, and market" barriers and risks were perceived as most impeding business performance. These barriers and risks specifically referred to the *limited access to finance*, as well as *low and unstable sales prices and market demand*. "Regulatory" barriers and risks, referring to the *imposed constraints on the use of substrates for rearing* and *the use of insects in feed and food products*, followed in terms of perceived importance. "Operational" barriers and risks mainly related to *the lack of mass rearing techniques* resulting in *insufficient production scale* for insect-based feed producers. Results from dynamic risk perception further revealed that stakeholders were generally optimistic towards the future, in particular when it considered "operational" and "financial, cost, and market" risks. To mitigate risks, stakeholders across chain stages mostly applied risk management strategies related to investments in technologies aimed at ensuring a consistent quantity, quality, and hygiene of production.

Chapter 5 evaluated the robustness of three potential generic business models for insect production: (1) full-liner *H. illucens* production for pet food, (2) decentralised *H. illucens* production for aquafeed, and (3) *T. molitor* processing cooperative for food. The robustness of these models was assessed through a Business Model Stress Test conducted in four focus groups with European experts from Belgium, Germany, the Netherlands, and southern Europe. The stress test included an impact assessment of six future scenarios on the robustness of business model components. The considered scenarios included uncertainties regarding regulations on the use of side streams, insect welfare regulations, and sustainability requirements and energy prices. The results of the impact assessment were summarised in heat maps, presenting the rated impact on the robustness of each business model component, which were further described using the experts' reasoning of their given impact ratings. Comparison of the robustness of the three business models revealed that the full-liner *H. illucens* production for pet food and the *T. molitor* processing cooperative for food were regarded more robust compared to the decentralised *H. illucens* production for aquafeed. Differences in robustness were primarily related to the customer segment, value proposition, and revenue and cost structure of the business models. Results further showed that, in general, the presence of strict regulations was considered to have the least negative or even a positive impact on the business models for pet food and food, while this was less pronounced for the business model for feed. With respect to energy and sustainability, experts expected that the business models' robustness would be negatively impacted by rising energy prices, while implementation of sustainability requirements could have a positive impact by serving as a competitive selling argument.

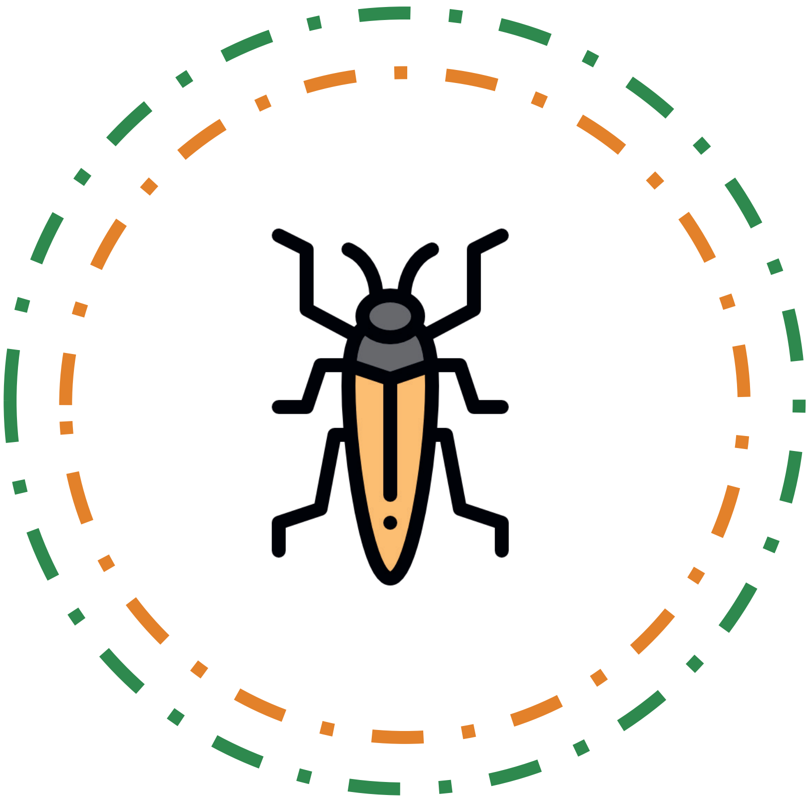
Chapter 6 synthesised and discussed results for the three themes: (i) economic performance, highlighting the lack of profitability for small-scale *T. molitor* businesses and the main operational cost components of labour and feed; (ii) risks and uncertainties for which it elaborated on the main perceived risks for actors throughout the insect supply chain; and (iii) business models in which context the added value of a cooperative was discussed and considerations were offered regarding the (economic) viability of upscaling as a potential solution for the insect sector in Europe. Chapter 6 further proposed recommendations for policy makers and businesses. Policy makers were suggested to support the development of smaller-scaled mechanised systems, prioritise the design and implementation of regulations, investigate in the feasibility of large-scale production systems, and to foster enhancement of consumer acceptance. Businesses were encouraged to: develop low cost small-scale technologies, prioritise intra chain and inter chain collaborations, and focus on a high level of transparency within the chain and towards consumers.



The main conclusions of this thesis are:

1. Key operational costs of insect production for feed and food in Europe included feed and labour costs (Chapter 2).

2. Sales prices of insects were related to the geographical market location, market type (feed or food), and volume of products sold (Chapter 2).
3. Small-scale *T. molitor* production in the Netherlands was considered not profitable, unless a large share of own (unpaid) labour was employed (Chapter 3).
4. Small-scale *T. molitor* production in the Netherlands presented large heterogeneity for nearly all profitability indicators (Chapter 3).
5. Across the insect supply chain in Europe important perceived "financial, cost, and market" risks encompassed difficulties to obtain finance, and pricing and demand uncertainties, while important perceived “regulatory” risks were related to restrictions on used inputs and marketed outputs (Chapter 4).
6. Regarding the dynamics of perceived risks, stakeholders expected a reduction in business risks, particularly concerning "operational" and "financial, cost, and market" risks, while perceived "regulatory" risks were expected to increase across nearly all supply chain stages of the European insect supply chain (Chapter 4).
7. The business models full-liner *H. illucens* production for pet food and *T. molitor* processing cooperative for food were considered more robust compared to decentralised *H. illucens* production for aquafeed due to differences in customer segments, value proposition, revenue structure, and cost structure (Chapter 5).
8. In general, the implementation of strict regulations on the use of side streams and insect welfare were perceived more positive for the robustness of business models, as compared to liberal or absence of regulations (Chapter 5).
9. Reducing the risks from insufficient market demand and consumer acceptance of insect-based food products were expected to become more challenging when incorporating low-value side streams due to increasing risks related to safety and quality variations (Chapters 2-5).
10. The acquisition of further data concerning side-stream availability, safety measures, economic viability, and environmental implications of small- and large-scale production systems is imperative for positioning insect production within feed and food markets and enabling effective competition with other industries (Chapters 2-5).



# Appendices

## List of publications

## Acknowledgements

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## List of Publications

**Niyonsaba, H.H.**, Höhler, J., Kooistra, J., Van der Fels-Klerx, H.J., and Meuwissen, M.P.M., 2021. Profitability of insect farms. Journal of Insects as Food and Feed, 7(5), 923-934.

**Niyonsaba, H.H.**, Höhler, J., Van der Fels-Klerx, H. J., Slijper, T., Alleweldt, F., Kara, S., Zanoli, R., Costa, A.I.A., Peters, M. and Meuwissen, M.P.M., 2023. Barriers, risks and risk management strategies in European insect supply chains. Journal of Insects as Food and Feed, 9(6), 691-705.

<u>Non-refereed</u>

Blanken, K., Evers, A., Groeneveld, I., **Niyonsaba, H.H.**, Ouweltjes, W., Verkaik, J., Vermeij, I. and Wemmenhove, H., 2022. KWIN 2022-2023: Kwantitatieve Informatie Veehouderij. (Handboek / Wageningen Livestock Research; No. 46). Wageningen Livestock Research. Wageningen.

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**Niyonsaba, H.H.**, Höhler, J., van der Fels – Klerx, H.J., Meuwissen, M.P.M., 2023. Best practice: key strategies for insect supply chain stakeholders to mitigate demand risks of insects and derived products. Available at https://susinchain.eu/wp-content/uploads/2023/05/Best-practice-Risk-management.pdf.

**<u>Conference posters and presentations</u>**

**Niyonsaba, H.H.**, 2021. Barriers and risks for large-scale commercialization of insect proteins for food and feed in Europe. (Conference presentation) EAAP conference 2021, Davos, Switzerland.

**Niyonsaba, H.H.**, 2023. Profitability of insect production for *T. Molitor* farms in the Netherlands. (Conference poster) EAAE conference 2023, Rennes, France.

**Niyonsaba, H.H.**, 2023. Robustness of business models for insect production in Europe. (Conference poster) SUSINCHAIN symposium, Wageningen, the Netherlands.

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My journey through my PhD program resembled a long run, with challenging uphill climbs, exhilarating downhill sprints, and serene stretches of stability. My main motivation for pursuing a PhD was twofold: first, to demonstrate my ability to work on one topic for a four-year period, and second, to make a meaningful contribution to the realm of sustainable agricultural development. As I embarked on this journey back in 2019, the duration and distance ahead seemed challenging, yet it is hard to realise that I have already crossed the finish line. Even though the medal (in this case being the cover of this thesis) bears my name, I would not have achieved this without the help from many cheerleaders along the route and fellow runners running (part of) this journey together with me, whom I would like to express my gratitude to below.

First of all, my supervising team deserves large credit; the team coached and paced from the start to the end, some periods more intensively than others. Even though many of the meetings had to be held online, they were always pragmatic, constructive, motivating, and not to forget in good spirit. I extend my thanks to you for your patience in listening to my ideas, for steering me in right directions to timely reach the finish line, for motivating me to undertake various activities, and for encouraging me in seeing the relevance of this journey and its outcome.

*Miranda Meuwissen,* when I first met you in the course on Risk analysis (MSc program) I was impressed by your practical way of teaching and you were a great inspiration for me. Doing this PhD under your supervision was a great opportunity for me. Your dedication and enthusiasm in your work (which extended to my research) inspired me. Even during moments when I felt like taking a break from this enduring race because I wondered who would profit from this research, your passion helped me to see the practical relevance of the results and to steadily resume my journey. Thank you *Miranda* for your detailed and constructive feedback, your practical solutions, and encouragements. I have appreciated the space and autonomy you gave me in conducting the work and the support in multiple aspects related to work as well as private life, your supervision truly felt as a personal training aiming to gain strength and to deliver the work with confidence.

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## About the author

Hilde van den Hoorn (1993) was raised on a farm close to the forest in Elspeet, a small town on the Veluwe. In 2011 she completed her secondary education at the Jacobus Fruytier Scholengemeenschap in Apeldoorn. After one year of studying Medicine and one gap year in which she worked on personal development, she started her BSc in Nutrition and Health at Wageningen University. During her bachelor studies, she enjoyed staying for seven months in Ethiopia to learn the culture and do voluntary work. After her return, she completed her BSc program (2017) with a thesis on Pyridoxin supplementation. She continued her studies with a MSc program in Food Safety (supply chain safety). As part of this program she wrote a thesis entitled: Logistics related food safety and quality challenges and opportunities in the East African milk supply chain. In 2019, she completed her studies with an internship on the Food Safety and Quality department of The Kraft Heinz Company in Nijmegen.

In December 2019, Hilde started her PhD research in the Business Economics Group of Wageningen University on the Economic Viability of Insect Production for Feed and Food in Europe. She was supervised by prof. Dr ir M.P.M. Meuwissen, prof. Dr ir H.J. van der Fels-Klerx, and Dr J. Höhler. Her PhD project was part of the Horizon 2020 project SUSINCHAIN, which was coordinated by Dr ir. T. Veldkamp. Within her PhD project, Hilde conducted different insect-related studies and presented her results on scientific conferences amongst which the EAAP conference in Davos (2021) and the EAAE conference in Rennes (2023). Additionally, she presented the results of her work frequently in organised sessions for SUSINCHAIN, the Ministry of Agriculture, Nature, and Food Quality, and other business organisations such as Foodvalley, NIK, and VENIK. In addition to her PhD research, she participated in a 'side project' on the economic feasibility of insect production of horticultural side streams. During the PhD trajectory, she enjoyed supervising BSc and MSc students, as well as assisting in education activities.

In general, her enthusiasm lies in the realm of sustainable food supply chains, enhancing food security, quantitative data, analysing practically relevant problems, and providing science-based solutions to address real-world challenges. She is looking forward to continuing her career path in international food and bio-based system research focused on the named topics, with a desire to drive a positive change in the society. In her free time, she finds peace in the serenity of the forest through running, mountain biking, or taking long walks. Outside the forest, she recharges from spending time with close friends, engaging in deep conversations, losing her energy through dancing, diving into personal development literature, and tuning into a diverse range of inspiring podcasts.

## Education certificate

**Henderike Heléne van den Hoorn**
**Wageningen School of Social Sciences (WASS)**
**Completed Training and Supervision Plan**

Wageningen School of Social Sciences

| Name of the learning activity | Department/Institute | Year | ECTS* |
|---|---|---|---|
| **A) Project related competences** | | | |
| **A1 Managing a research project** | | | |
| WASS Introduction Course | WASS | 2020 | 1 |
| *'Barriers and risks for insect production'* | EAAP, Davos, Switzerland | 2021 | 1 |
| '*Profitability of insect production for T. molitor farms in the Netherlands'* | EAAE, Rennes, France | 2023 | 1 |
| Scientific writing | Wageningen in'to Languages | 2021 | 1.8 |
| Attendance BEC PhD meetings | BEC | 2019-2023 | 1.5 |
| **A2 Integrating research in the corresponding discipline** | | | |
| Econometrics (AEP 21306) | WUR | 2020 | 6 |
| Quantitative data analysis: multivariate techniques (YRM 50806) | WUR | 2021 | 6 |
| **B) General research related competences** | | | |
| **B1 Placing research in a broader scientific context** | | | |
| Summer school: risk analysis and risk management in agriculture: updates on modelling and applications | WASS | 2021 | 3 |
| Academic publication and presentation in the social sciences | WASS | 2022 | 4 |
| **B2 Placing research in a societal context** | | | |
| Article on barrier and risk perception | Food and Agribusiness magazine | 2023 | 1 |
| Presenting results to stakeholders in various Dutch insect-related organisations and institutes | NIK (Barneveld, 26/10/2021), Foodvalley (online, 09/02/2022), Ministerie van Landbouw, Natuur en Voedselkwaliteit (The Hague, 13/12/2022), VENIK (online, 25/01/2023). | 2019-2023 | 1 |
| **C) Career related competences/personal development** | | | |
| **C1 Employing transferable skills in different domains/careers** | | | |
| Teaching and supervision of BSc and MSc students | BEC | 2019-2023 | 4 |
| Project and time Management | WGS | 2020 | 1.5 |
| Teaching and supervising thesis students | WGS | 2022 | 0.3 |
| Training: start to teach at university | WGS | 2023 | 0.3 |
| **Total** | | | **33.4** |

*One credit according to ECTS is on average equivalent to 28 hours of study load

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