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Life cycle assessment of insect production based on Norwegian resources

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Livsløpsvurdering av insektproduksjon basert på norske ressurser

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Preface

This thesis concludes my work to obtain the title of Master of Technology in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. The work comprises a life cycle assessment (LCA) of insect production based on Norwegian resources and conditions for production. The specific Norwegian conditions modelled in this study reflect the plans of insect production company Invertapro and their partner BIR. These plans include the industrial production of the insect species yellow mealworm and black soldier fly based on locally available side-streams and waste resources on the West coast of Norway.

I would like to thank BIR for giving me the opportunity to work with insects and waste management at Invertapro's facilities in Voss in the summer of 2018. This experience provided me with valuable insight of insect production as a technology for waste management and protein production and motivated me to pursue this as the topic of my master thesis. A special thanks to Toralf Igesund at BIR for interesting discussions on the role of insects and the waste management sector in the circular economy. I would also like to thank the team at Invertapro for including me in their team and providing me with extensive information and motivation for this work. My supervisor Sigrun Jahren has also provided me with guidance, and my co-supervisor Johan Berg Pettersen has given me invaluable help with the LCA modelling and associated discussions.

Abstract

The continued growth of the global population is putting an unsustainable pressure on natural resources, and the need for action to ensure sustainable food production is urgent. Sustainable development is dependant on effective management and utilization of available resources such as energy, water and raw materials. Insects have been promoted as a source of high-quality protein which could potentially help to address these challenges.

The production of insects in Western cultures is not extensively wide-spread, but has been gaining attention over the past years for several reasons. First and foremost, insects are very efficient at turning their feed into nutritious biomass in the form of high-quality protein. Insects can also utilize materials which are usually considered to be wastes, such as organic household wastes and agricultural residues, thereby recycling otherwise wasted nutrients back into the food chain.

The intrinsic characteristics of insects thus promote their production as a sustainable alternative to both food and feed commodities, but as the insect industry is still relatively new, particularly in Europe, the potential environmental impacts from such production systems have not been extensively quantified yet. Some studies do exist, but the impacts reported varies greatly, which means that it is difficult to draw general conclusions on the environmental performance of such systems. In connection with the planned up-scaling of insect production on the West Coast of Norway, a life cycle assessment (LCA) is therefore preformed in this study to provide insight into the environmental impact pathways from such systems in a Norwegian context.

A system model for automated production of the two insect species yellow mealworm and black soldier fly, intended for use as food and feed respectively, was developed in this study based on a literature review and contact with insect producers and research facilities in Europe. The LCA identified the feeding substrate provided for the insects and the heating demand for the production facilities as hotspots for environmental impacts in this system. This highlights the importance of using low-quality waste streams as feed for insects and also the need for designing insect factories with efficient heat solutions for production in Norway.

Comparison of insect-derived products to other commercial food and feed ingredients showed that the potential environmental impacts from Norwegian-produced insect products as food were significantly lower than similar impacts from other animal protein sources. When compared to feed, insect products showed similar or higher impacts than most comparable alternatives, both plant-based and animal-based. Nevertheless, insects should not be disregarded as a potentially environmentally beneficial feed ingredient, as this study was limited to a few selected impact categories, and does therefore not necessarily reflect the full picture.

Sammendrag

Den fortsatte veksten i den globale befolkningen setter et uholdbart press på verdes naturressurser, og det er ytterst nødvendig å iverksette tiltak for å sikre bærekraftig matproduksjon. Bærekraftig utvikling er avhengig av effektiv forvaltning og utnyttelse av tilgjengelige ressursser som energi, vann og råvarer. Insekter har blitt fremmet som en kilde til høy-kvalitets protein som potensielt kan bidra til å løse disse utfordringene.

Produksjon av insekter er ikke spesielt utbredt i vestlige kulturer i dag, men har fått økende oppmerksomhet de siste årene av flere grunner. Først og fremst er insekter svært effektive til å omdanne fôr til næringsrik biomasse i form av høy-kvalitets protein. Insekter kan også utnytte organiske materialer som vanligvis anses for å være avfall, for eksempel organisk husholdningsavfall og jordbruksrester, og dermed gjenvinne næringsstoffer som ellers ville gått tapt tilbake i næringskjeden.

Insekter iboende egenskaper fremmer dermed produksjon av disse virvelløse dyrene som en bærekraftig alternativ til både mat og fôrvarer, men ettersom insektindustrien fortsatt er relativt ny, spesielt i Europa, har de potensielle miljøpåvirkningene fra slike produksjonssystemer ikke blitt spesielt godt kvantifisert ennå. Noen studier eksisterer men de rapporterte miljøpåvirkningene varierer sterkt, noe som betyr at det er vanskelig å trekke generelle konklusjoner om slike systemers miljøprestasjoner. I forbindelse med den planlagte oppskaleringen av insektsproduksjon på Vestlandet i Norge blir en livsløpsvurdering (LCA) derfor gjennomført i denne studien for å gi innsikt i mulige miljøpåvirkningsveier fra slike produksjonssystemer i norsk sammenheng.

En systemmodell for automatisert produksjon av de to insektartene gul melorm og svart soldatflue, beregnet for bruk som henholdsvis mat og fôr, ble utviklet i denne studien basert på en litteraturstidue og kontakt med insektprodusenter og forskningsanlegg i Europa. LCAen identifiserte fôringssubstratet for insektene og oppvarmingsbehovet for produksjonsfasilitetene som hotspots for miljøpåvirkning i dette systemet. Dette understreker viktigheten av å bruke lavkvalitets avfallsstrømmer som fôr til insekter samt behovet for å designe insektsfabrikker med effektive varmeløsninger for produksjon i Norge.

Sammenligning av insekt-produkter med andre kommersielle matvarer og fôringredienser viste at de potensielle miljøbelastningene fra norsk-produserte insektprodukter brukt som mat var vesentlig lavere enn tilsvarende påvirkninger fra andre animalske proteinkilder. Sammenlignet med andre fôringredienser viste det seg at insektprodukter har tilsvarende eller høyere miljøpåvirkninger enn de fleste sammenlignbare alternativer, både plantebaserte og dyrebaserte. Insekter bør allikevel ikke avfeies som en potensielt miljømessig gunstig fôringrediens, da denne studien var begrenset til noen få utvalgte miljøpåvirkningskategorier, og derfor ikke nødvendigvis reflekterer hele det sammensatte bildet.

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Chapter 1

Introduction

1.1 Background

The introduction of the Circular Economy Action Plan by the European Commission in 2015 signaled a fundamental shift in the way we utilize and valorize our resources. Circular economy is characterized by resource efficiency and closing loops, where the goal is to keep resources circulating in loops through re-use and recycling (European Commission, 2017b). This kind of economy represents a more sustainable alternative to the "use and discard" mentality which has been prevalent for the past decades. With the circular economy package, Europe has begun the work of adapting to the challenges of an increasing population and limited natural resources.

At the nexus of these challenges is the provision of food for an increasing global population. The affluence level is expected to increase alongside the population increase, which implies higher consumption of energy- and emission intensive food commodities (FAO, 2009). In total, it is estimated that the global food production has to increase by approximately 70 % to facilitate the projected population of 9 billion people in 2050 (FAO, 2009; UN, 2017). Feeding this population will require massive amounts of land, water, energy and fertilizer, further pressuring and exhausting resources already under heavy stress. Climate change affecting agricultural productivity, pollution from use of fertilizers and pesticides, deforestation to allow for agricultural expansion, overfishing and excessive wild harvest as well as dwindling freshwater resources are serious challenges for the global world population (Dossey et al., 2016). To achieve sustainable development for both current and future generations, measures have to be implemented to ensure better and more efficient utilization of the resources at our disposal. We need to re-think how we feed both ourselves and the animals which we eat.

A technology which is currently getting increasing attention in Europe is the farming of insects for combined waste management and feed and food production. Insects can utilize organic waste streams as feed, and efficiently convert this feed into high quality protein and fat. In practice, this means that insects can be used to turn a resource stream which has traditionally been considered as waste, into new food and feed products. Using insects as a form of bio refinery thereby circumvents the whole waste concept by re-introducing an otherwise low-valued resource stream into the value chain as high-value products. This way, important nutrients are recycled back into the food web, which lowers the need for virgin materials. Large-scale production of insects does as such fit well within the circular economy concept, and presents an innovative technology for keeping important nutrients in the loop.

In Norway, the production of insects is particularly interesting with respect to its potential for production of high-quality protein feed. The supply of traditional feed ingredients such as fishmeal, fish oil and soybean meal is challenged by increasing prices and large environmental impacts (Veldkamp et al., 2012). Fish meal and fish oil is mainly made from wild caught pelagic fish, a resource which is severely threatened by overfishing (FAO, 2014b). Simultaneously, alternative plant based feed ingredients such as soybean meal requires large ares for cultivation, which is often at the expense of native people and forest, and which in many cases competes with use for human consumption. Plant based alternatives also often have an unfavourable nutritional composition, making it less than ideal for use in aquaculture feed (Sørensen et al., 2011). To facilitate the projected increase in Norwegian aquaculture production there is a need for new, sustainable feed ingredients. Lock et al. (2016) summarized that the use of insect meal in the diet of different fish species such as African catfish, turbot, tilapia and rainbow trout has been tested with promising results. Similarly, Belghit et al. (2018) found that insect meal could be included in feed for Atlantic salmon, a fish species of which Norway is the largest producer worldwide (Sørensen et al., 2011), without negative effects on growth and nutritional qualities.

Simultaneously, Norway will be facing the same challenges as the rest of the world with respect to the provision of food for its growing population. The production of animal products such as meat and dairy is commonly associated with relatively high environmental impacts in terms of both greenhouse gas emissions and natural resource use, prompting the need for alternative animal protein sources also for human food (Huis and Oonincx, 2017). Although insects are not traditionally a part of Western diets, over 1900 different insect species have been documented as edible for humans, and over 2 billion people all over the world eat insects as a regular part of their diet (Van Huis et al., 2013). For humans and animals alike, insects are nutritious. High in energy and protein, insects are also rich in micro nutrients such as the minerals copper, iron, magnesium, sink, and phosphorus as well as the vitamins riboflavin, folic acid and biotin (Rumpold and Schlüter, 2013a; Payne et al., 2016). In addition to their nutritional qualities, insects have other characteristics which makes insect farming interesting compared to farming of other livestock. Insects have short life cycles, fast reproduction rates and high feed conversation efficiencies, enabling high yields at low cost to resources such as water, land and feed (Van Huis et al., 2013). The direct emissions of greenhouse gases from insects have also been measured to be lower than direct emissions from other livestock such as cattle and pigs, further promoting insects as a sustainable source of animal proteins for people as well as animals (Oonincx et al., 2010).

All in all, insect production fits well within the scope of the circular economy, and shows potential as a contribution towards global food and feed security. The insect sector is however only just getting started in Europe, and much research is still needed to facilitate large-scale production of insects for food and feed purposes. Scaling up existing insect production in Europe requires interdisciplinary knowledge and collaboration. Insect production is as such an innovative technology responding to two intertwined challenges, namely the nutrients which are currently lost through poor utilization of organic waste resources and the need for more sustainable production of protein for food and feed.

1.2 Aim of the study

The demand for more sustainable feed ingredients for the aquaculture sector combined with the need for new treatment technologies for organic waste has sparked the interest for insect production in Western Norway. BIR[1], the waste management company for the Bergen region in Western Norway, is currently collecting organic waste in a combined waste fraction with residual waste. This combined fraction is sent for incineration at BIR's incineration plant as of today. However, as a part of the circular economy package, Norway, in line with EU regulations, will impose mandatory source separation and treatment of organic waste from households and businesses (Miljødirektoratet, 2018). BIR must therefor establish new treatment practises for handling the organic waste fraction separated by households and business in the region.

In Norway, anaerobic digestion (AD) has been promoted as a climate friendly treatment option for food waste (Norwegian Ministry of Climate and Environment, 2014). However, a study performed by COWI and BIR in 2013 found that AD treatment of food waste in Western Norway will only provide limited environmental gains at high cost (Igesund et al., 2014). The lack of possible markets for the bioresiduals produced from AD was the main cause for the limited environmental benefits. The market for bioresiduals in Western Norway is limited because of the regulations pertaining to the use of bioresiduals from AD as fertilizer. The fertilizer regulations in Norway state that bioresiduals from AD can only be used as fertilizer on fields where it is ploughed into the ground after it has been applied. Effectively, this restricts the use of bioresiduals from AD to fields used for grain cultivation, which is not extensively practised in Western Norway due to climate and soil conditions. The climate benefits of AD treatment cannot fully be realised if the bioresidual is not used, as this would effectively just turn one waste stream, i.e. food waste, into another waste stream, i.e. inapplicable fertilizer. BIR is therefor in the process of investigating other treatment options for organic waste from their residents and businesses which can possibly provide greater environmental benefits at more reasonable costs.

One of the technologies explored by BIR as an alternative to AD is the use of insects to upcycle organic waste into food and feed. In collaboration with the insect production company Invertapro[2], located in Voss, they are now testing insect production as a means of *quality recycling*. This interest in insect production for waste management purposes is timely, as the Norwegian aquaculture industry has expressed keen interest in the use of insects as a new, protein-rich and sustainable feed ingredient. Norwegian aquaculture feed manufacturer Skretting has already started using insect meal as a feed ingredient, and other manufacturers such as BioMar, are also expressing their interest (Skretting, 2018; Gracey, 2019). There are also esteemed Norwegian research institutions such as NIBIO (Norwegian Institute of Bioeconomy Research) and NIFES (Norwegian Institute of Nutrition and Seafood Research) involved in research projects to facilitate the use of insects for waste management and protein production in Norway. The Aquafly project, which finished in 2018, explored the use of insect meal as a new, sustainable feed ingredient for the aquaculture sector (NIFES, 2015). The Entofôr project, which started in 2017, is focused on providing the tools necessary to establish a Norwegian insect industry which can utilize waste resources as feed for insects to produce food and feed (NIFES, 2017). Alas, there are interested and active actors in the whole value chain necessary to establish an insect production industry in Norway today.

[1] Bergensområdets Interkommunale Renovasjonsselskap. https://bir.no/om-bir/english/
[2] https://www.invertapro.com/

However, none of the mentioned actors have focused on quantifying the environmental impacts of an insect production system in a Norwegian context. It is, after all, the concept of insect production as an environmentally sustainable alternative to other waste management options and protein production systems which is one of the main drivers fuelling the interest in this novel industry. **The aim of this study is therefor to explore the environmental impacts of an industrial insect production system based on Norwegian resources**. Previous studies have shown that the environmental impacts from insect production system varies greatly with geographic location, feeding substrate and end use of the insects (Halloran et al., 2016). The focus of this study is therefore to investigate insect production technologies and the potential impact of the production processes on the environmental performance of the system as a whole. According to IPIFF (International Platform of Insects for Food and Feed) and Halloran et al., the full environmental benefits of insect production can only be realized for automated, industrial size systems. This study therefor aims at quantifying the impacts associated with an industrial scale system established in the Western region of Norway, where Invertapro and BIR plan on up-scaling insect production.

Life cycle assessment (LCA) was chosen as the methodical framework for this study, as this is a widely recognized tool for quantifying environmental impacts for systems and services alike. More specifically, life cycle thinking has become increasingly important for both the development and evaluation of a sustainable approach to fundamental functions in our society, such as food production and its inherent waste management (Notarnicola et al., 2017). For the past twenty years, LCA methodology has been used to identify how agricultural systems can ensure sustainable production and consumption of food commodities (Notarnicola et al., 2015). Building on this established practise, LCA was chosen as the tool for quantifying potential environmental impacts from an insect production system. This allows for comparison of insect production and its derived products to other food production systems and products. Such comparisons are becoming increasingly important as efforts are made to improve current practises to ensure better resource utilization.

Life cycle analysis is used as a systemic tool for quantifying potential environmental impacts of the system, and to answer the following research questions:

1. Which production process(es) contribute(s) most to the environmental impacts from a Norwegian insect production system?

2. Which parameter(s) from the overall insect production system influence(s) the total environmental performance?

3. Can any system specific choices be made when planning and designing an insect production system, especially with respect to energy supply and feeding substrate, to lower the total environmental impact of the system?

4. How does the environmental performance of insect products compare to other food and feed commodities?

To answer these question, a gate-to-gate life cycle assessment will be performed based on a model description of an industrial size insect production facility located in Norway. The model will include all processing steps in insect production, from feed preparation, through reproduction and rearing of live insects, to processing into finished products. The goal is that this study can inform important design parameters when such facilities are designed and operated in Norway in the future. Sensitivity scenarios were also developed to investigate the effect of different feeds for insects and different energy solutions on the potential environmental impacts of the system as a whole. Insect production is for the time being a novel approach to waste management and protein production, particularly in Norway, and a life cycle assessment can be useful in establishing this industry's role in the circular economy.

Chapter 2

Theory

2.1 Life cycle assessment

Life cycle assessment (LCA) has been developed as a tool for understanding the links between impacts on the environment and the products we produce, use and eventually waste (ISO, 2006). This methodological framework can as such be used to identify hotspots for environmental impacts in the life cycle of products, so that these hotspots can be addressed and possibly improved to decrease impacts. This identification is based on environmental impact pathways, such as the use of resources and the release of substances to air or waterways, and follows the product through its life cycle from extraction of raw materials to final waste disposal and management.

By following a standardized procedure including four phases, the results are given as potential quantified environmental impacts presented for different impact categories. The four phases are 1) definition of goal and scope, 2) life cycle inventory analysis (LCI), 3) life cycle impact assessment (LCIA) and 4) interpretation, as visualized in figure 2.1. The LCA framework thus enables a holistic approach to the quantification of the environmental performance of products, and by adhering to a standardized procedure also enables comparisons of different products on a fair basis. The framework in its entirety is standardized by the International Organization for Standardization (ISO), and can be found in standard ISO 14040:2006. This standard forms the basis of the environmental impact assessment performed in this study, and some of the main characteristics of the framework is presented here based on the ISO standard.

2.1.1 Goal and scope definition

The system to be assessed is presented in the goal and scope part of an LCA. To put the system into context, the reason for preforming the assessment and the intended target group should be presented. For most systems, there are some limitations to the number of processes and possible pathways that can be included within a reasonable time-frame and level of detail. System boundaries and data requirements must therefore be stated, defining which processes are included within the scope of the assessment. Any assumptions made or limitations presented in the study should be evident in the goal and scope phase.

To properly define the goal and scope of an LCA, a functional unit (FU) must be defined for the

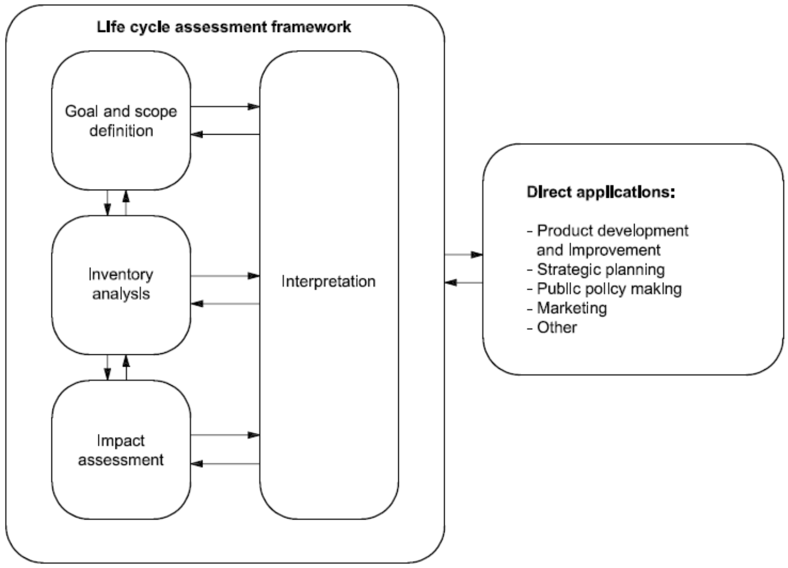


Figure 2.1: The four phases of a life cycle assessment. Reproduced from ISO (2006).

system. The FU represents the the performance characteristics of the product that is assessed. If allocation is used to distribute environmental burdens from a multi-functional system, the allocation procedures should be documented, so that this can be taken into consideration in the interpretation of the final results. The impact categories chosen to represent the final results must also be described in this phase.

2.1.2 Inventory analysis (LCI)

The data used to quantify the potential environmental impacts of the system are collected in an inventory analysis. Here the origin of the data and any calculation steps preformed to obtain the necessary data quality is described. Inputs and outputs from the system are described and quantified, and typically includes raw materials, energy and any other resources used as input to the system.

The products, co-products and wastes derived from the system are also quantified, including emissions and other forms of outputs from the system. Typically, manufacturing of products and services require the direct use of natural resources such as land area, which must also be quantified. If there are any multi-functionality in the system, the allocation procedures described in the goal and scope phase must be implemented in the inventory analysis.

2.1.3 Impact assessment (LCIA)

The inputs and outputs quantified for the system in the LCI must be translated into representative environmental impact categories. The mathematical principles which underline this translation process are relatively simple, and consists mainly of matrix multiplication. For large systems containing many unit processes these matrix can become quite large, and software tools have been developed to perform these calculations even though they can be performed by hand.

Different methods exist for performing the calculations assigning the inventory data to different impact categories. Some impact categories, such as climate change (also known as global warming potential), are similar across methods, while some impact categories in different methods represent the same potential environmental impact, but are expressed using different indicator elements. An example of this is eutrophication potential, which is expressed in terms of g NO_3 equivalents when using the IMPACT 2002+ method and in kg P equivalents when using the ReCiPe method. In IMPACT 2002, nitrogen is used as the indicator element for quantifying potential eutrophication impact, while in ReCiPe, phosphorous is used as the indicator element.

The impact assessment follows five steps, of which the first three are mandatory. The impact categories which are to be used must be defined first, followed by the *classification* step where the inventory data are assigned to the chosen impact categories. The final mandatory step is *characterization*, in which the category indicators are calculated. When these three steps are completed, the final LCIA results are obtained. Additional steps can be performed where the results are re-calculated relative to specified reference information, which is known as *normalization*. Weighting can also be performed, where some impacts are considered to be of higher importance or more relevant, and the results are adjusted accordingly.

2.1.4 Interpretation

When the results have been obtained through the life cycle impact assessment, the only phase remaining is the interpretation of the results. The interpretation should consider all phases of the LCA, not only the impact assessment, as modelling choices made in the first two phases will influence the results obtained in the impact assessment. The results should align with the goal and scope defined in the first phase. When interpreting the results, emphasis should be put on the fact that any results obtained through an LCA represent *potential* impacts, as it is not possible to account for all indirect environmental impacts 100 % accurately, no matter how detailed the inventory.

In the interpretation, reflections and explanations should be made regarding the limitations in the other phases, so that relevant conclusions can be drawn to facilitate reasonable recommendations. The four phases of the LCA framework thus represent an iterative process, where the different phases influence the others and some aspects might be reconsidered throughout the process. This is illustrated by the arrows going both ways in figure 2.1.

The LCA framework as described here forms the basis for the work preformed in this study. The goal and scope was briefly stated in the introduction, and will be further documented in chapter 3. The inventory analysis is also preformed in chapter 3, and the impact assessment follows in chapter 4. The interpretation phase is documented in chapter 6, facilitating the conclusion made in chapter 7.

2.2 Multi-functionality of insect production systems

Insects serve many purposes in the natural environment and are vital for upholding the ecosystems which we humans rely on. Van Huis et al. (2013) reported on the many functionalities of insects, including facilitating plant reproduction, waste biodegration and pest control, in addition to providing valuable products and inspiration for technology and engineering developments. Insects are crucial for plant reproduction through their role as pollinators, and thus essentially underpin all agricultural activities we depend upon for food. Additionally, insects provide some of the most extensive waste management services in nature, breaking down dead plant matter and manure so that the nutrients become available to other organisms instead of volatilizing directly to the atmosphere.

Inspired by these natural mechanisms, humankind has started domesticating insects for more direct utilisation of these services, creating a multi-functional production system. Using waste resources as input to such a production system, insects can make use of the nutrients embodied in the waste, and turn it into valuable nourishment for humans and animals alike. Insect production systems are undeniably inspired by the role of insects in nature, and their potential for contributing to more sustainable management of resources has been gaining increasing attention over the last years (Diener et al., 2011; Premalatha et al., 2011).

Insect production is considered to be particularly interesting due to their small size, fast reproduction rates, high survival rates and their short life cycles (Gahukar, 2016). These traits contribute to insects being easy and efficient to cultivate. Combining this with the fact that insects are cold-blooded, which allows them to convert their feed into nutrient-rich biomass very efficiently, and that insects can be fed with a large variety of organic material, it seems that the interest in insects which is currently blooming is well founded. Insects are thus equipped to serve multiple functions in the circular economy, namely treatment of organic waste resources as well as providing protein rich animal protein.

Insect production thus addresses two challenges at the same time, namely the conflict of land allocation for food, feed and fuel production to accommodate a growing population with increasing living standards, as well as the environmental impacts associated from insufficient or inefficient nutrient recovery practices from organic waste.

2.2.1 Using insects for waste management

As many insects have voracious appetites and can feed on many different organic materials (often also decaying material), insects show great potential for waste management of organic waste streams. In practise this means that insects have the ability to recycle important nutrients back into the food chain, and in this was the production of insects introduces a new level to the waste hierarchy, as can be seen in figure 2.2. This is a new approach to waste management, as few other waste management technologies currently in use manages to upcycle food waste into new food.

2.2.2 Insects as food and feed

The International Platform of Insect for Food and Feed (IPIFF) has estimated that the total protein production from insects can reach 1 213 490 tons by 2025 (IPIFF, 2018). This is almost a 1000-fold increase from today's production of 1900 tons. Such an increase might seem unattainable, but given that 122 insect-related actors were identified by Dossey et al. already in 2016, it is not impossible. This signals a shift from insect production as novelty to an industry gaining a solid foothold, also in Europe.

The insect industry is also getting traction in Norway. Norwegian aquaculture feed manufacturer Skretting has stated that the main limiting factor for the use of insect protein in fish feed formulations is that there is currently not enough available amounts. Skretting has expressed

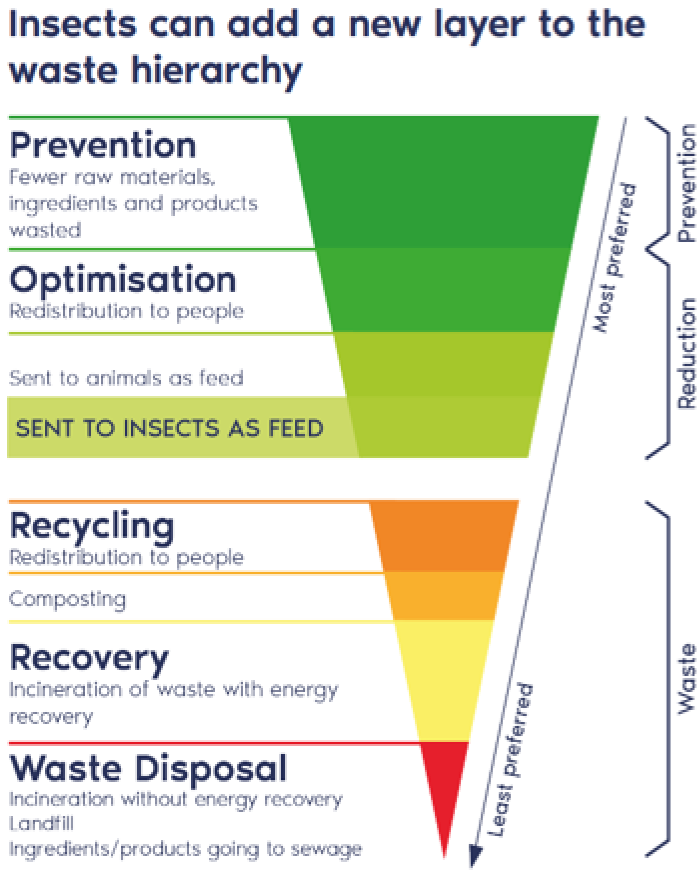


Figure 2.2: Insect production in the waste management hierarchy. From IPIFF (2018).

a need for the production of at least 100 000 tons by European producers for use by Skretting alone by 2022 (Skretting, 2018). This highlights the need for commercializing and up-scaling this industry to supply the demand for this new protein rich ingredient.

For it is the protein content of the insects which is primarily advocating for its use in food and feed (Veldkamp et al., 2012). The protein content varies between insect species, and depends on the feeding substrate provided for the insects. Insects also generally have a relatively high content of fat, as can be seen in table . This table lists the crude protein content of three insects species currently farmed for food and feed purposes, in addition to protein and fat content for comparable food and feed commodities. From the table it can be seen that the protein and fat content of insects are comparable to other feed ingredients such as fish meal and soybean meal, while insects generally have higher protein and fat content than other common animal protein foods.

Insects as feed

Insects have been suggested and tested as a feed ingredient for many animals, including fish (Belghit et al., 2018; Lock et al., 2016; Van Huis et al., 2013), poultry (Józefiak et al., 2016; Benzertiha et al., 2019) and pigs (Veldkamp and Bosch, 2015). For some animals, such as fish, insects are a part of the natural diet of animals living in the wild, such as wild salmon, and including insects in feed formulations is thus more natural than for example the inclusion of soy beans (Van

Table 2.1: Crude protein and fat content of common insect species and conventional food and feed products

Protein source	Crude protein (%)	Crude fat (%)	Source
Insects			
Hermetia illucens (Black soldier fly)	35-57	35	Veldkamp et al. (2012)
Musca domestica (Common housefly)	43-68	4-32	Veldkamp et al. (2012)
Tenebrio molitor (Yellow mealworm)	44-69	23-47	Veldkamp et al. (2012)
Feed ingredients			
Fishmeal	61-77	11-17	Veldkamp et al. (2012)
Soybean meal (defatted)	49-56	3	Veldkamp et al. (2012)
Food commodities			
Chicken	17.8	6.0	Siemianowska et al. (2013)
Egg	12.5	9.7	Siemianowska et al. (2013)
Beef	20.1	0	Siemianowska et al. (2013)
Fish (rainbow trout)	18.6	0.7	Siemianowska et al. (2013)

Huis et al., 2013). Taking the Norwegian market into consideration, the most interesting aspect is probably the use of insects as feed for farmed fish in aquaculture. As previously stated, the Norwegian aquaculture industry has expressed a keen interest in insects for feed. Lock et al. (2016) and Belghit et al. (2018) have tested the use of insects in the feed for Atlantic salmon, which Norway is the largest producer of (Sørensen et al., 2011). Both studies found that insect meal did not cause unwanted impacts on fish health parameters, and concluded that insects meal from the insect species black soldier fly is an appropriate feed ingredient for Atlantic salmon. All in all, the use of insects in feed has great potential, and might even improve animal health (Sánchez-Muros et al., 2014).

Insects as food

Van Huis et al. (2013) emphasises three reasons for why we should eat insects: 1) insects are a healthy and nutritious alternative to other animal protein foods, 2) lower environmental impact due to insects emitting fewer greenhouse gases, using their feed more efficiently and requiring less land than other livestock and 3) offers livelihood opportunities, particularly in poorer regions of the world. The nutritional quality of insects have been found to be favourable for human consumption, and includes a favourable composition of fatty acids as well as amino acids, essential vitamins and minerals (Siemianowska et al., 2013). In a study of six insect species, including the yellow mealworm, Payne et al. (2016) found that insects were not significantly healthier than other meat products, but insects were not found to be less healthy than meat either. One of the main barriers to utilizing insects as food for direct human consumption in Western countries is thus not the nutritional aspects of this protein source, but rather the disgust and fear often associated with the practice of eating insects (Van Huis et al., 2013).

2.3 Environmental impacts from insect production systems

Van Huis et al. (2013) pointed out the low environmental impact of insects compared to other livestock products as a reason for why we should eat insects. However, quantifying the environmental impact of an insect production system depends on many factors, including which insect species is used, the type of feed provided for the insect and its origin, the level of automatizing and mechanization in the production, where the production takes place as well as transportation involved in the value chain (Halloran et al., 2016). To date, few publications exist in which these factors have been characterized, and the environmental performance of insects production systems is thus currently not well documented, particularly in comparison to other livestock production system. The need for studies investigating the potential environmental impacts from insect production systems is thus large. The statement of insects as a truly sustainable commodity needs to be founded in verifiable science if it is to support the establishment of a strong insect industry in Europe.

Studies currently available on the environmental performance of insect production systems all follow the life cycle assessment (LCA) approach. This methodology is generally accepted as an appropriate framework for quantifying environmental impacts through the whole life cycle of products and services, and is commonly used for food products. However, there is a knowledge gap withing this field in the insect industry, which was addressed by Halloran et al. (2016) in their review of LCAs of edible insects. This review pointed out that existing studies on environmental impacts from insect production are very heterogeneous in many aspects, which makes it difficult to compare results and draw any general conclusions for insects production systems. However, it is possible to reflect on parameters and production conditions which have been studied until now to shed light on what affects the environmental performance of insect production systems.

2.3.1 Feeding substrate

Production and transportation of feed is known as one of the most important environmental impact pathways for livestock production worldwide (Gerber et al., 2013; Halloran et al., 2016). The production of feed usually requires large areas of land and substantial amounts of water and fertilizer, and is often associated with degradation of land areas, deforestation and biodiversity loss, as well as contributing to pollution of water and air (Gerber et al., 2013). If similar feed resources is used for insects as for other livestock production systems, the same undesirable impacts would naturally be associated with insect production as well. However, due to the efficiency with which insects transform their feeding substrate into biomass, these impacts could potentially be substantially lower for insect production systems (Halloran et al., 2016). This efficiency is enhanced by the cold-blooded nature of insects, which allows them to utilize their high metabolism directly for feeding rather than maintaining their body temperature(Oonincx et al., 2015; Halloran et al., 2016). The high metabolism and cool-blooded nature also allows many insect species to feed on waste streams.

Shifting the feeding substrate for insects from conventional feed resources, or even foodstuffs which are edible for humans, to material which is otherwise unsuitable for food or feed shows potential for lowering environmental impacts associated with feed. This was highlighted in the study by Oonincx and De Boer (2012), the first environmental impact assessment of an insect production system preformed, in which conventional feed resources were used as feeding substrate for the insects. The conventional feed resources used were carrots, mixed grains and brewery waste, the production and transportation of which contributed the most to all three impact categories investigated in this study, namely global warming potential (in kg CO_2 equivalents), energy use (in

MJ) an land use (in m^2 of arable land). This implies that the use of waste resources or other non-utilized resources holds the potential to substantially lower these impacts. However, it is important to underline that utilizing waste as feed for insects does not automatically make insect production preferable to any other livestock production system. This only highlights one option for potentially lowering environmental impacts from the system, and must be evaluated for each specific system and setting (Halloran et al., 2016). Using waste resources, such as for example by-products from food production, or organic waste from restaurants, as feed for insects could possibly only serve as a re-direction of an already suitable utilization of the resource, and might therefore not lead to lowered impacts for the supply chain as a whole.

2.3.2 Production parameters

For optimal growth and survival of farmed insects, special attention must be paid to some parameters of the production. Similar to other livestock production systems, the design and operation of the rearing activities will influence both the productivity of the system as a whole, as well as the potential environmental impacts of the system. To achieve optimal productivity at the lowest possible cost to the environment, LCA can be used as a tool, preferably early in planning and design processes of production facilities, to ensure sustainable production practises (Roffeis et al., 2017).

Sustainable production practises are essential to achieve industrial-size production systems based on automated operation. Insect production systems are currently characterized by manual labour, which are keeping production costs high and limiting the production capacity of individual producers. Ortiz et al. (2016) reported that if a mechanization level of 80 % is attained, a more predictable supply of products of high quality can be assured, which is an important step in making insects competitive with other animal products. Automation will also provide optimization opportunities for the individual processes in the production, further promoting insects as high-quality animal products (IPIFF, 2018).

Even though the automation of processes is essential to large-scale insect production, it also involves the use of more advanced technology, which can be associated with larger resource demand in terms of for example energy. Higher energy consumption will affect the environmental impacts associated with the production as a whole, which must be taken into consideration both when designing and evaluating insect production systems. This is of particular interest when insect production systems are compared to other livestock production systems (Halloran et al., 2016).

In addition to the effects of automatising of production processes, the effects of maintaining the specific environmental conditions required for insect production must be considered. The cold-blooded nature of insects means that they use all their energy to digest their feed, and insects are thus dependant on their surroundings to maintain their body warmth (Premalatha et al., 2011). This means that insects are dependant on stable, optimal temperatures to thrive. For many insect species, these optimal temperatures are quite high, which means that there is a high heating demand for the production facilities, all year around. This will also influence potential environmental impacts, as many European countries are characterized by relatively cold climates, accentuating higher energy consumption for heating purposes, particularly during the winter season.

Many insects are flexible and can survive even if the production parameters such as temperature is not optimal, but this should be avoided for extended periods of time, as sub-optimal conditions extends the life cycles. This might in turn require extra input of resources such as feed and water, while simultaneously reducing the output from the system, which can further increase environmental impacts (Halloran et al., 2016).

2.3.3 Review of existing LCAs of insect production systems

The number of publications existing on the subject of potential environmental impacts from insect production systems are limited as of today. A total of ten publications were found to address this subject through the use of life cycle assessment, but due to large methodological differences, these studies are difficult to compare. The assumptions applied, functional units used, the data sources and system boundaries applied as well as general LCA approaches used differ greatly (Halloran et al., 2016). Smetana et al. (2016) highlighted that one of the main challenges of comparing these studies is founded in the principal goals defined in the different studies. Some of the studies focus on the use of insects as a waste treatment option (Roffeis et al., 2015; van Zanten et al., 2015), some focus on the potential of insects as human food (Oonincx and De Boer, 2012) and others on production of insects for use in feed (Muys et al., 2014). Other studies combine different functions of insects, such as the combined waste management and protein production by use of insects (Smetana et al., 2016; Salomone et al., 2016; Smetana et al., 2019). Based on an overview over existing LCA studies on insect production systems as presented in (Smetana et al., 2016), a similar overview over the currently available studies is presented in this study. The overview can be found in table 2.2, in which the studies which have been performed also after the article by Smetana et al. (2016) was published have been included.

Table 2.2: Results of LCA impact assessment from different studies, adapted from Smetana et al. (2016). FU = 1 kg of insect protein meal.

LCA studies	**Insect species**	**Impact assessment method**	**Feed substrate**	**Midpoint impact categories**		
				GWP[1] [kg CO2 eq.]	**Energy use [MJ]**	**Land use [m2 arable]**
Oonincx and De Boer (2012)	Mealworm	Separate indicators	Mixed diet	3.5	44.32	4.68
Thévenot et al. (2018)	Mealworm	Total Cumulative Energy Demand and CML-IA	Mixed diet	3.75	141.29	4.13
Muys et al. (2014)	BSF	ReCiPe	Brewery wastes	–	13.4–64.06	0.01–0.04
Smetana et al. (2015)	BSF	ReCiPe and IMPACT 2002	Food wastes	7.1–7.55	80.0–101.0	3.75–3.8
Salomone et al. (2016)	BSF	CML	Variety of diets	2.1	15.1	0.05
Smetana et al. (2016)	BSF	ReCiPe and IMPACT 2002+	Variety of diets	1.36–15.1	21.2–99.6	0.032–7.03
Rustad (2016)	BSF	ReCiPe	Food wastes	0.17	–	0.00
Smetana et al. (2019)	BSF	IMPACT 2002+	Agriculutral by-products	7.911 - 8.37	–	19.945 - 22.479
Roffeis et al. (2015)	Housefly	ReCiPe	Pig manure	–	159.85–288.15	2.79–5.32
van Zanten et al. (2015)	Housefly	Separate indicators	Poultry manure and house waste	0.77	9.3	0.032

The large variations found within the field of LCAs of insect production systems is highlighted in the table. Particular attention should be given to the large differences found in the results reported. The two studies on mealworms report of similar impacts for global warming potential (GWP) and land use, but the energy use is very much higher in the study performed by Thévenot et al. (2018). For the studies investigating environmental impacts of black soldier fly (BSF) production systems the variations are extremely large within all impact categories presented here.

Impacts range from 0.15 kg CO_2 eq reported for GWP in Rustad (2016) to 15.1 kg CO_2 eq in Smetana et al. (2016), from 13.4 MJ reported for energy use in Muys et al. (2014) to 101 MJ in Smetana et al. (2016) and from 0 m^2 arable as reported in Rustad (2016) to 22.479 m^2 arable reported in (Smetana et al., 2019). For the housefly production systems impacts are reported to vary from 9.3 MJ of energy use in van Zanten et al. (2015) to 288.15 MJ as reported in Roffeis et al. (2015). The land use reported by van Zanten et al. (2015) for housefly production is also substantially lower than that reported by Roffeis et al. (2015), whom reported of 0.032 m^2 arable and 5.32 m^2, respectively.

These differences can be explained by the varying goals defined, functional units used, insect species investigated, the geographical location of the production system and the origin of the data used for modelling the systems. Data quality ranges from laboratory studies to large-scale industrial production systems and extensive reliance on literature. This makes it difficult to draw conclusions, and it also emphasises the many modelling choices facing the individual LCA practitioner aiming at assessing environmental impacts from an insect production system. However, some guidelines can be provided based on the review of LCAs done of insect production systems preformed by Halloran et al. (2016).

The review states that a proper description and definition of the system to by modelled, including the life stages of the specific insect species used should be provided. Representative data, preferably collected *in situ* should be obtained if possible, as well as the selection of realistic alternatives for comparisons where this is relevant. The review further underlines that it is important to include all relevant processing steps, such as for example the post-processing of harvested insects into marketable end-products. Evaluation the environmental performance of insect systems should also be based on a suitable range of different impact categories to facilitate a wholesome evaluation of potential impacts. To deal with the multi-functionality of insect production systems, Halloran et al. (2016) suggested the use of at least two functional units for insect production systems, based on at least two of these three attributes: mass, nutrient content or economic value.

2.4 The insect species under investigation

Over 1900 species of insects have been identified as edible (Van Huis et al., 2013). Over 2 billion people, divided over 3071 ethnic groups in 130 countries primarily in Asia, Latin America and Africa eat insects on a regular basis (Costa-Neto and Dunkel, 2016; Van Huis et al., 2013). However, the practise of eating insects is not common in western culture (DeFoliart, 1999). Insects are considered to be “novel” food in the European Union (EU), which means that insects were not commonly used for human consumption within the EU/EAA before May 15th 1997 (Mattilsynet, 2016). The EU, and also Norway as a member of the EAA, is therefor applying the cautionary principle. Only 7 insects species are currently allowed for food and feed production in the EU (European Commission, 2017a). Of these species, there are two which have received much attention in Europe as candidates for large-scale production for use in food and feed, namely the yellow mealworm (*Tenebrio molitor*) and the black soldier fly (*Hermetia illucens*) (Veldkamp et al., 2012; Van Huis et al., 2013).

Both species can efficiently utilize organic waste streams as feed, are high in protein and are relatively easy to cultivate, making them good candidates for waste management and protein production (Dossey et al., 2016; Van Huis et al., 2013). With respect to end use both species show potential for use in feed and food, though the black soldier fly is best suited for feed purposes (Van Huis et al., 2013), while the mealworm is considered a good candidate for human consumption (Oonincx et al., 2015; Siemianowska et al., 2013). By producing both species at the same time, a producer can specialize the rearing of yellow mealworm for food applications and black soldier fly for feed purposes. Farming both species at the same time also provides flexibility and reduces the risk for the producer. The two species prefer different diets, enabling the producers to handle a large variety of organic waste streams when producing both species. Insect producers are also particularly vulnerable to disease outbreaks due to the small size and vast number of individuals insect which makes it difficult to isolate sick animals in case of disease. By farming the two insects species separately at the same time, an insect producer will always have one insect species to fall back on if the other should be affected by disease. The characteristics of the two species is described here.

2.4.1 Yellow Mealworm (*Tenebrio molitor*)

The yellow mealworm can be found all over the world, and is commonly know as a pest of stored grains and cereals (Ghaly and Alkoaik, 2009; Broekhoven, 2015). It is relatively easy to cultivate, and has been reared for fish bait and reptile feed purposes, especially in the USA, since the 1950s (Gahukar, 2016; Morales-Ramos et al., 2019).

Life cycle Ribeiro et al. (2018) have preformed a review of scientific literature for the optimal conditions for mass rearing of the yellow mealworm and reports on the four life stages of the lifecycle; egg, larva, pupa and adult. Generally, the different life stages are kept in separate trays for production. An adult colony of beetles is needed at all times to uphold reproduction to maintain the colony, and the larval stage is when most of the bioconversion of the feeding material takes place. Of the four stages, it is the larva which is the desired product when producing mealworms for food and feed. The review by Ribeiro et al. is used for reference when referring to life cycle traits of the yellow mealworm.

Beginning from the adult stage of the life cycle, each adult yellow mealworm female can lay between 250 and 1000 eggs, with an average of 250-500. The eggs are sticky, and are laid singly or in clusters so that they attach to the substrate which the mealworms are living in, or on the floors and walls of the trays that the mealworms are kept in. The temperature in which the mealworm is reared has large impacts on its development time. Optimal conditions for eggs to hatch is at 26 - 30°C, in which the eggs will hatch in approximately 4 days. At 15°C the eggs can take as long as 34 days to hatch. Similarly, the larval stage lasts for around 57 days in a controlled environment, but could take up to 629 days in natural conditions in an ambient temperature environment. The pupal stage lasts from 6 to 20 days, after which the pupa emerges as an adult. 3 days after the adult has emerged it begins mating and oviposition of eggs. The adult stage lasts for 16 - 173 days, making the total average life cycle time of the mealworm between 75 and 90 days.

Feed Natural feed for yellow mealworm consists of dry substrates such as cereals and grains. A moisture content of 5- 15 % in feed for mealworms is typically used. Mealworms can also feed on agricultural by-products and milling residues such as meals, brans, bread, crackers, wheat straw, brewer's spent grain and distillers dried grain (Kim et al., 2016; Ghaly and Alkoaik, 2009). A benefit of mealworms living in their feed in all stages of the life cycle is that they cannot climb out of the trays they are cultured in, as long as the tray is of an appropriate material (typically plastic). This is what makes the yellow mealworm both easy to manage and valuable from a waste management perspective. Additionally, the yellow mealworm requires very little water to thrive, as they can take up water both from their feed and the atmosphere. In mass-rearing it is common to provide the mealworms with water in the form of a wetter feeding substrate in addition to the dry substrate, in combination with keeping the relative humidity (RH) in the room high.

Environmental conditions In the previously mentioned review by Ribeiro et al. (2018), the main environmental conditions affecting the rearing of yellow mealworms is described, including optimal relative humidity (RH) level, temperature, population density and reaction to light. High RH is important both to satisfy the larva's need for water and to ensure fast larval growth, and the optimal level is between 60 and 70 % RH. Generally mealworms have the highest growth rates at between 90 and 100 % RH, but combined with an optimal rearing temperature of 25 - 28°C this favours bacterial growth and mould and is therefor not ideal.

When rearing mealworms it is important to note that mealworms produce metabolic heat when feeding, and high population densities of larva can increase the temperature in the rearing trays significantly, in some cases to lethal levels (Morales-Ramos and Rojas, 2015). Too high population densities can also lead to cannibalism and inhibit development into the pupa stage, as well as reduce the growth rate of the larvae because of competition for food (Ribeiro et al., 2018). Moreover, reproduction rates are heavily affected by the density of adult beetles. Morales-Ramos et al. (2012) found the optimal density of adult yellow mealworms to be 8.4 adults/dm^2.

Generally, mealworms withdraw from daylight by burrowing into their feeding substrate and emerging to the surface of the substrate when it becomes dark. Long-day conditions were reported by Kim et al. (2015) to be favourable for both larval development, hatching times and pupation rates, with an optimum of 14 hours of daylight and 10 hours of darkness in a period of twenty-four hours. However, under constant lighting conditions the mealworms tend to stop responding notably to differences in lighting (Ribeiro et al., 2018).

2.4.2 Black Soldier Fly (*Hermetia illucens*)

The black soldier fly (BSF) is indigenous to tropical regions of America, but can also be found as a part of the natural fauna in warmer regions in other other parts of the world (Čičková et al., 2015). For the past 50 years the BSF has been getting increasing attention for various applications including manure control, house fly management in chicken production facilities, feed for fish and swine and waste management, as summarized by Marshall et al. (2015).

Life cycle The life cycle of the black soldier fly consists of five life stages; egg, larva, prepupa, pupa and adult, which have been described by Ortiz et al. (2016). As for the mealworm, the different life stages of the BSF are kept separate for production, mainly divided into an adult colony for reproduction and the mass-production of larvae. One distinct difference between the mealworm and the BSF is that the adult BSF can fly, which requires a cage to prevent escape. The cages must be at least 1 m^3 to fulfill the mating requirements of the adults. Otherwise the adult BSF are easy to cultivate, as they do not feed in this life stage but rather depend on energy stored in their body reserves from the larval stages. This characteristic is crucial for production of BSF in temperate regions such as Norway where the species does not naturally exist. Because the adult fly does not feed, it is not a potential carrier of diseases and the risk of farming it is therefor substantially lowered.

The adults live for approximately 5-8 days, in which they mate and the female lays 400-800 eggs. The female only lays eggs once, and the eggs are laid in dry cracks and crevices in close proximity to feeding material, so that the larva can start feeding at once after hatching (Dortmans et al., 2017). The egg hatches into a larvae after around 4 days in optimal rearing conditions, while too low temperatures will significantly extend the time until hatching and reduce survival rate (Tomberlin et al., 2002; Ortiz et al., 2016). Under optimal conditions the larvae will feed greedily on the provided feeding material over period of 14-16 days. If the rearing conditions are not ideal, i.e. the temperature is not optimal or there is shortage of food, the larvae can extend its life cycle up to four months (Dortmans, 2015). This resilience is an important trait for mass-rearing of the BSF which provides flexibility in the case of sub-optimal production parameters for a period of time. The larva of the black soldier fly displays migratory behaviour when it nears the pupation stage. When the larva enters the prepupal stage it stops feeding and empties it guts while migrating out of the feeding substrate in search of a dry and dark place where it can pupate (Diener et al., 2011). Combining this migratory behaviour with the larva's ability to climb inclines of up to 40°, the BSF can be self-harvesting if the production facilities are designed to take advantage of this behaviour(Banks, 2014). The BSF larvae is harvested just before it enters the prepupa stage, where most of the larva are harvested and processed into food and feed, while 1 - 10 % are allowed to pupate into pupa and then adults to reproduce and maintain the colony. The total average life cycle time of the black soldier fly is 37 - 54 days (Mutafela, 2015; Oonincx et al., 2015).

Feed The black soldier fly larva is a voracious feeder, and have been reported to consume up to 500 mg of fresh matter per larva per day (Makkar et al., 2014). The natural feed for BSF is a large variety of decaying organic materials such as food waste and manure (Diener et al., 2009; Van Huis et al., 2013). Different biomass reduction percentages have been reported in different studies, ranging from 50 % reduction reported by Barry (2004) to Diener et al. (2011) showing that household food waste was reduced by 65 - 75 % when processed by black soldier fly larva and 78 % biomass reduction as reported by Li et al. (2011). Where the mealworm prefers dry feeding substrates, the black soldier fly larva prefers relatively wet feed, where a moisture content of 70 - 90 % is reported to benefit larval development (Liu et al., 2018). There is however a compromise between the moisture content of the feed and the residue that remains in the trays after the larvae enter into the prepupal stage.

The BSF larva live in their feed in trays similar to those used for mealworms, but where the mealworm larva eats essentially all the feed it is given, the BSF larva will leave a residue in the tray. The quality and the moisture content of the feeding substrate will affect the remaining residue, which will influence how easy it is to separate the prepupa from the residue if this is done mechanically using a sieve (in place of using the migratory behaviour of the prepupa). In experiments performed by Diener et al. (2011) the residue had a moisture content of 82 - 86 %, which gave off a foul smell because water accumulated in the bottom of the tray while whole pieces of undigested food waste covered the top of the tray. This was reported to obstruct the larva's access to the feed and thus reduced larval growth, effectively reducing the final yield of prepupa and the total amount of waste reduced by the larva. Cheng et al. (2017) found that 70 - 75 % moisture content in the feed was optimal for enabling sieving of the residue after the bioconversion. As sieving is currently the method used in most commercial production facilities in Europe as it is easy to automate such a process, this is important to consider.

Heavy metal contamination has also been highlighted as a parameter of particular importance with regards to feeding of the black soldier fly. Heavy metals such as cadmium, lead and zinc has been shown to bioaccumulate in the BSF larva if present in high concentrations in their feed (Diener et al., 2015). Though the BSF larva can be seriously affected by heavy metal in its feed, the BSF larva can also reduce contamination in the feed. Harmful bacteria, such as *E. coli* and *Salmonella*, has been shown to be significantly reduced in materials processed by BSF larva (Makkar et al., 2014).

Environmental conditions Native to tropical regions, the black soldier fly a requires warm, humid environment to develop in a healthy and efficient manner. Barry (2004) and Makkar et al. (2014) reported of an optimal temperature range of 29 - 31 °C at 50 - 70 % relative humidity, while Chia et al. (2018) found the optimal temperature to be 30 °C and the total viable temperature range to be 15 - 40 °C. The growth and survival rates are significantly lowered at both very low and very high temperatures. Barry (2004) demonstrated that BSF reproduction requires sunlight to be successful. For commercial mass-production of BSF, providing direct sunlight is not always an option, and research is currently being conducted on the use of artificial lighting to stimulate mating. Already in 2010, Zhang et al. (2010) showed that a 500 W quartz iodine lamp could simulate sunlight sufficiently to induce mating. Later both Oonincx et al. (2016) and Heussler et al. (2018) recommended the use of LED lights as this showed best results with regard to oviposition of eggs, larval survival and energy efficiency after extensive experiments with different light sources. The larva, on the other hand, prefers a shaded environment, and crawls deeper into their feeding substrate if the surface is exposed to light (Dortmans et al., 2017).

2.5 Insect production technologies

2.5.1 Development of the insect sector

Using insects as an ingredient in food and feed has been practised for a long time. In China insects have been eaten for around 3200 years according to Yi et al. (2010) and Costa-Neto and Dunkel (2016) reports of insect consumption in ancient Greece. Van Huis et al. (2013) tells of Mayan civilizations rearing honeybees both for the production of honey but also for the use of the bees themselves as food. Generally, the consumption of insects is most widespread in warmer climates such as Asia, Latin America and Africa where the tradition of gathering insects from the wild for food have been strong, particularly among indigenous people (DeFoliart, 1999). Most insects used for both food and feed today are harvested from the wild (Van Huis et al., 2013; Costa-Neto and Dunkel, 2016). However, domestication and commercial production of some insect species have begun both in the previously mentioned areas as well as in Western countries (Van Huis et al., 2013; DeFoliart, 1995).

Whereas insects are considered traditional food ingredients which are gathered from the wild in some regions, the practise of farming insects in closed facilities has gained more attention in

Western countries. The mass-rearing of insects begun in the US in the 1940's to produce sterile insects for pest control (Rumpold and Schlüter, 2013b; Gahukar, 2016). Later, in the 1970s and 1980s, insects were produced commercially as live feed for reptiles and other exotic pets in the US, before entering the pet food market as a feed ingredient (Gahukar, 2016). Commercial mass-production of insects is now gaining interest all over the world as a technology for production of sustainable ingredients for both food and feed. However, even though the practice of both eating and farming insects for various purposes has existed for quite some time now, the insect industry, particularly in Europe, is still working to establish itself.

A challenge associated with establishing industrial scale mass-production of insects is to ensure safe and traceable material as feed for the insects. Though insects are biologically able feed on a wide range of organic materials, the risks associated with consumption of insects reared on different materials is not well documented yet. The European Food Safety Authority(EFSA) therefore performed and released a risk profile on insects as food and feed in 2015. The risk profile addresses potential biological and chemical hazards as well as the effect of different feeding substrates and processing methods on food and feed safety of insect products. Based on the conclusions from EFSA in addition to existing literature, currently applicable EU regulations and experiences from European insect producers, the International Platform of Insects for Food and Feed (IPIFF) has released a "Guide on good hygiene practises for European Union (EU) producers of insects as food and feed". This guide aims to help insect producers to achieve food and feed safety throughout the value chain. The main elements of insect production technology will be described here, based on the recommendations from the IPIFF guide, literature and correspondence with insect producers and research institutions in Europe.

2.5.2 Process overview

Generally, insect production systems are very similar to other animal production systems. The animals being farmed (in this case insects) need water and feed to grow, and in turn excrete waste material. The insects are affected by physical and environmental production conditions, and certain safety boundaries need to be in place to prevent sickness and pest outbreaks (European Food Safety Authority, 2015). A general process overview over the production activities in an insect production facility can be found in figure 2.3. The system consists of four main processes, including rearing processes where the colony is maintained through reproduction, followed by the sorting/harvesting of the appropriate life stage when the cycle of the respective insect species is completed. After harvest the insects are post- processed and finally distributed as finished products. To ensure safe and efficient production, many parameters must be monitored and controlled underway in the production process, as illustrated in the figure. These parameters might include environmental conditions as mentioned in section 2.4, such as temperature, relative humidity, light, ventilation, population density, food and water availability and consumption in addition to microbial contamination. The general outline of a production cycle for any insect species can be summarized as shown in figure 2.4. The different steps will be described in here.

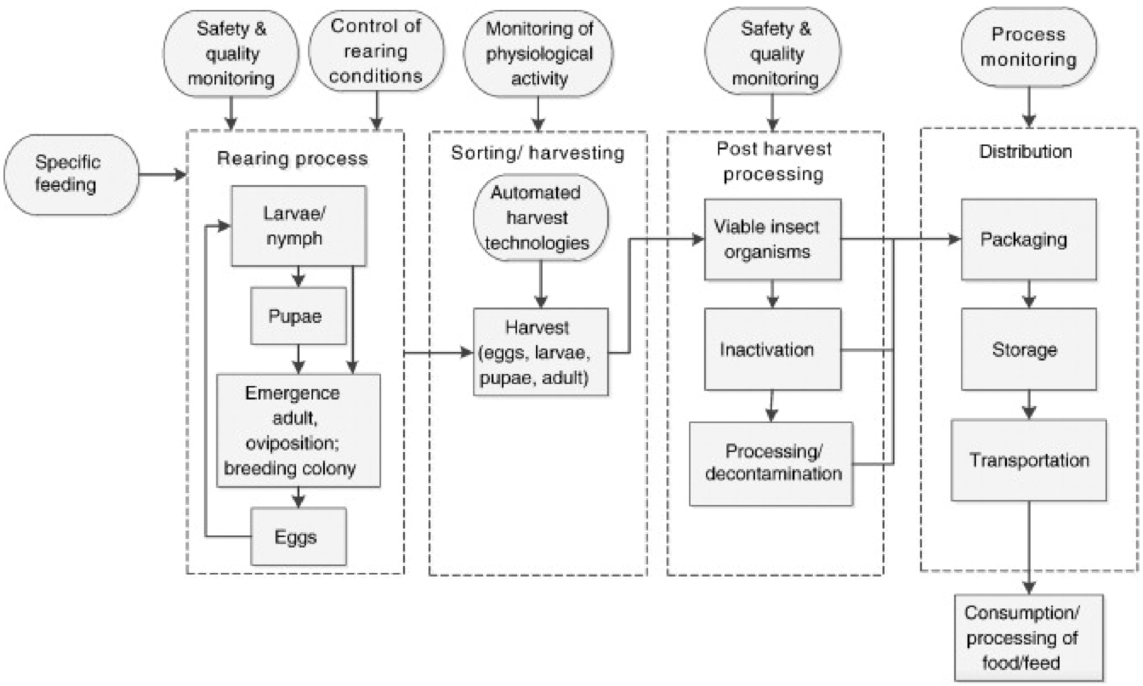


Figure 2.3: Schematic overview of insect production processes, reproduced with permission from Rumpold and Schlüter (2013b)

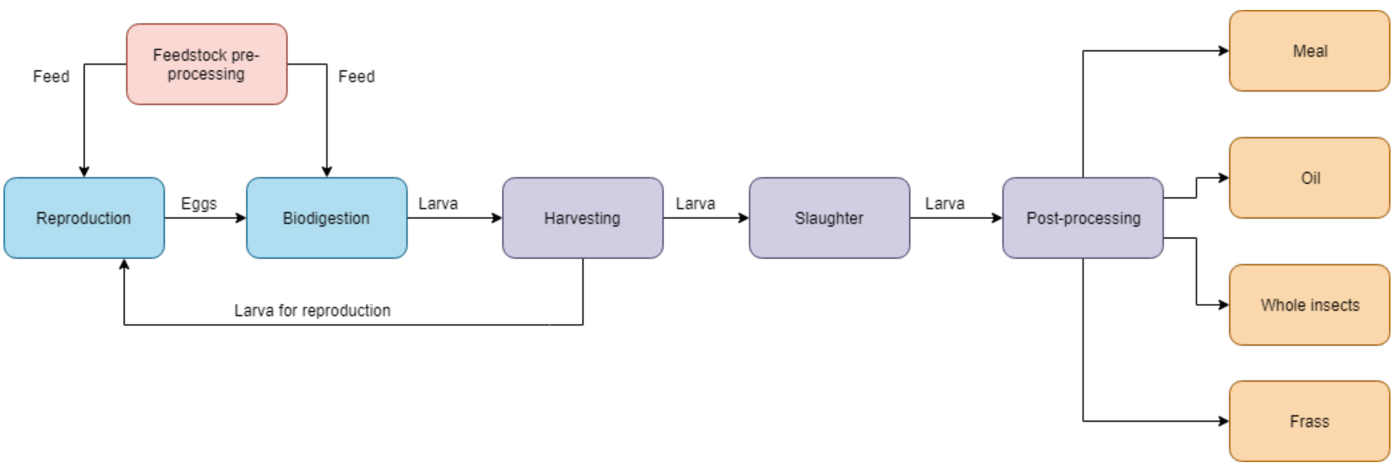


Figure 2.4: Processing steps of insect production

2.5.3 Feedstock pre-processing

Insects produced for use as food and feed are defined as farmed animals according to EU regulations, and the material given as food to insects is thereby also classified as feed (Mattilsynet, 2017). The material used as feed might be called feeding substrate, feedstock or simply feed, but common for all material intended for use as feed for any kind of livestock (farmed animals) is the general feed ban rules. According to Mattilsynet (The Norwegian Food Safety Authority), which is working in line with EU regulations, approved feed materials for insects are currently limited to materials of vegetal origin, with some pre-defined exceptions such as fishmeal, eggs and egg products, milk and milk based-products, honey and rendered fat. This means that for example food waste originating from restaurants, catering establishments and households are prohibited as feed for insects as per now. This is currently one of the limiting factors of insect production in Europe, as many organic waste streams which could potentially become new food and feed ingredients through insect processing are currently not allowed.

However, there are still many sources of organic material which can be used as feed for insects today, including former foodstuffs, by-products and side-streams of vegetal origin. Depending on the species farmed, most feed materials must be pre-processed to achieve homogeneity as well as appropriate moisture content and particle size of the substrate. When using waste streams and/or by-products from agriculture and food processing, this pre-treatment is particularly important, as there might be variations in the quantity and quality of the material throughout a production cycle. Insects generally have an appetite for a large variety of organic materials, but to achieve fast and healthy growth it is important to pay attention to the contents of the feed. Gligorescu et al. (2018) found that BSF will reduce feed intake and slow larval growth if the diet is unbalanced, such as too high in protein or too high in carbohydrate. Similarly, Rasmussen et al. (2016) found that the biomass growth of the mealworm larva was notably affected by different diets.

The pre-processing steps generally consist of mixing, grinding and potentially also de-packing if the material is packed in for example plastic packaging. Adding or filtering out water is also common to achieve proper moisture content for a given species. As previously mentioned, the mealworm thrives best on dry substrates of approximately 5 - 15 % moisture content, while the BSF prefers wet substrates of up to 90 % moisture content. In some cases, particularly for wet substrates, the feeding substrate must also be kept cold, potentially at freezing temperatures, to avoid spoilage of the material. For mealworms, which mainly feed on dry substrate, but also need water, often provided through a wet substrate, different pre-treatments might be necessary

If food wastes such as organic household waste is allowed for use in feed for insects sometime in the future, more comprehensive pre-treatment processing might be necessary. This is because vegetal organic material from pre-consumer stages of the food chain such as agriculture, food processing or retail which is currently allowed as feed is easier to control and trace than organic material sorted as food waste at consumer level. Johansen et al. (2018) reported that if food waste from households is to be used as feed for insects, pre-treatment must include sanitation of the feed material according to one of six pre-defined methods, as described in Regulation (EU) No 142/2011. A separation step specifically for the removal of foreign substances is also necessary to ensure that for example metal and plastic is sorted out. A pre-treatment step for household food waste will as such most likely resemble the pre-treatment step currently used in anaerobic digestion processing of similar organic wastes.

2.5.4 Reproduction

The design and operation of reproduction activities in an insect production facility will depend on the species farmed. Generally, efficient use of space to produce as many eggs as possible is the goal of any rearing operation. Providing the specific species with adequate rearing conditions are vital to the continuous production of any insect, and might include optimization of cages or trays, air flow, feeding substrate and egg collection methods (Ortiz et al., 2016).

Black soldier fly

The BSF adult is a fly, and therefore needs to be kept in a cage to prevent escape and to ensure that eggs are oviposited somewhere they can be collected. An example of a cage for adult BSF are shown in figure 2.5a, as is used by Inagro's research facility in Belgium (Coudron, 2019). The cage has a lighting fixture at the top to provide the necessary lighting required for reproduction, as described in section 2.4.2. The cage itself is fitted with a mesh which cages in the BSF flies. The green plastic object seen in the figure provides the flies with water (the adult BSF does not feed, and thus only needs to be provided with water). Under the water dispenser is a wooden chamber which provides a sheltered cavity for the females to deposit the eggs in. An egg collector, as shown in figure 2.5b is placed inside the chamber to provide crevices in which the females deposit their eggs. The collector is easy to take out from the cage to transfer eggs into feeding substrate in crates, where the eggs will develop into larvae. Underneath the cage there is a crate containing a mixture giving off a particular odor. This odor attracts the females to the chamber. This is necessary to "steer" the females in the right direction, as they can also deposit eggs for example in the cracks and crevices along the edges of the cage. Eggs deposited here are impossible to collect and will not survive due to the lack of feed. The sheltered cavity and the egg collectors in the reproduction cages are therefore crucial to the continuous production of BSF (Dortmans et al., 2017).

Yellow mealworm

The yellow mealworm adult is a beetle, and can be kept in crates similar to the crates used for growing larva. An example of a crate of mealworm beetles is shown in figure 2.6a. Ortiz et al. (2016) reports that the female mealworms deposit eggs on the bottom of the crate that they are reared in. The eggs are "glued" together in small clusters with a sticky substance, making the eggs stick to the feed in the crate (the crates are generally made of smooth plastic, making the tray bottom itself too slippery for the eggs to stick to). This characteristic is one of the challenges of mealworms production. When the eggs stick to the feed, they are at risk of being eaten by the beetles. Egg cannibalism is as such a continuous risk to the stable supply of mealworm eggs. Different methods are used in mealworm production systems to handle this challenge. Ortiz et al. (2016) describes a system proposed by Morales-Ramos et al. (2012) in which the bottom of trays containing adults are replaced by a screening mesh, allowing small larvae to fall through into a shallow tray kept underneath. This system is based on eggs surviving long enough in the tray with the beetles to hatch, and that the small larvae will be motivated by the movement of the adults to seek to the bottom to escape cannibalism.

Another solution has been proposed by Andersen and Berggren (2017) using a specially designed egg collector as shown in figure 2.6b. The egg collector is designed in a material which does not allow the eggs to stick to the surface. The dry feeding substrate intended for the adults is sifted in a sift with a mesh size of 500 - 700 μm before placing it in the egg collector. The egg collector is then placed in the tray, away from the wet feeding substrate. The dry feeding substrate will thus attract the adults into the egg collector, where they will oviposit in the feeding substrate. The substrate with attached eggs can then be sifted through the same sift to allow separation of the eggs from the substrate. The collected eggs can then be transferred to new trays and covered with feeding substrate to enter into the larva production cycle. Reproduction of mealworms can also be done in normal crates without any additional contraptions. This method requires the content of each

(a) BSF cage.

(b) BSF egg collector.

Figure 2.5: BSF reproduction equipment, courtesy of Inagro research facility, Belgium.

tray of beetles to be sifted often to separate out the eggs. This can be done through a succession of sifts with different mesh sizes, as suggested in a patent by Ynsect, one of the largest producers of mealworms in Europe (Comparat et al., 2018).

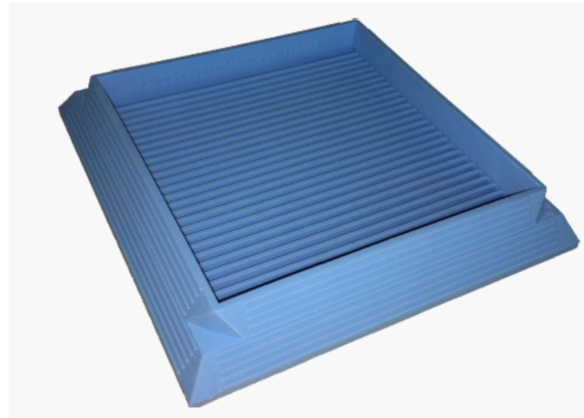
2.5.5 Bioconversion

Bioconversion is the processing step which represents the waste management properties of the insect production system. For most insect species this step is mainly preformed by the larva (IPIFF, 2019).

Feed conversion efficiency

The main activity in this production step is the conversion of the organic material into insect biomass. The efficiency of conversion from feed into body-mass by any animal is usually calculated as the feed conversion ratio (FCR) (Oonincx et al., 2015). Insects generally have high FCRs, i.e. they convert large amounts of their feed into biomass. This is one of the main reasons why insects are considered to be a sustainable alternative other animal protein sources. However, FCR differs

(a) Crate of yellow mealworm beetles, courtesy of Invertapro, Norway.



(b) Egg collector for yellow mealworms, courtesy of Danish Technological Institute.

between insect species and is dependant on the feed provided and the environmental conditions in the rearing facilities, among other things, and is generally difficult to compare across studies and systems (Halloran et al., 2016). As an example, Oonincx et al. (2015) reported that yellow mealworms can convert 22 - 45 % of the protein in their diet into body-mass and BSF can convert approximately 43 - 55 %, while poultry given optimal diets are only able to convert 33 %.

Insect excreta

As for any other form of livestock, insects also produce excreta, also known as frass, as a result of digesting their feed. For insects reared in crates, this means that the excreta is excreted into the crates together with the feeding substrate (Ortiz et al., 2016). The consistency of the frass varies with the insect species reared and the substrate given as feed, but is generally dry and relatively odorless. The frass is rich in nutrients, and is generally considered to have similar properties to organic fertilizer (Čičková et al., 2015; Van Huis et al., 2013; Zahn, 2017). For the yellow mealworm, which lives in primarily dry feeding substrate and also excretes a completely dry excreta, it is important to sieve out the frass from the crates at regular intervals during the bioconversion to prevent mite infestation and to fully embrace the potential economic value of this co-product (Ortiz et al., 2016).

Zong et al. (2015) designed an automatic screening machine for the specific purpose of screening yellow mealworm larvae from their excreta, as shown in figure 2.7, based on a sieving frequency of about every 15$^{\text{th}}$ day. However, different sieving frequencies are used by commercial insect producers, depending on the size of the crates, population density and feeding substrate. The BSF is provided with a wet feeding substrate, and the separation of larva, feed and frass is therefore not easily accomplished. As a result of this, BSF usually stay in their crate with both feeding material and frass until they are harvested. The larval stage of the BSF is much shorter than that of the mealworm, and the risk of mite infestation is thus much smaller. The BSF larva also reduce the moisture content of their feed radically through their feeding cycle. At harvest the

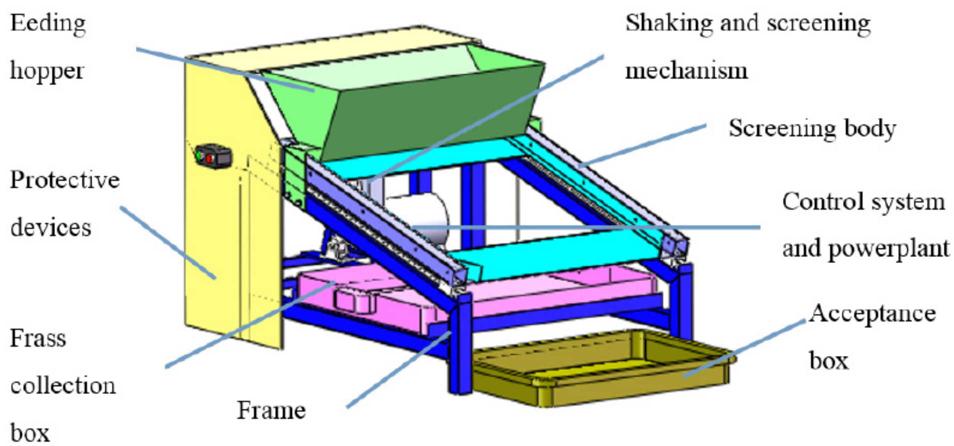


Figure 2.7: Screening machine for the separation of yellow mealworm larva and frass, as designed by Zong et al. (2015).

content of the crates is usually relatively dry and easy to separate into residue, containing frass and any potential feed leftovers, and larva by use of similar screening technologies as the machine in figure 2.7 (Coudron, 2019). Few studies exist on the actual performance of frass as a fertilizer, but initial trials on the use of fertilizer from BSF production suggests positive effects on plant growth (Zahn, 2017; Temple et al., 2013).

Energy requirements and space utilization

Due to the high temperature and humidity levels necessary for insect production, energy requirements of an industrial insect production facility might be relatively high compared to other types of livestock farming (Oonincx and De Boer, 2012). For countries such as Norway, this implies that heating is necessary in the winter months and cooling is needed in the summer (Ortiz et al., 2016). However, this high energy requirement can be somewhat compensated for by the efficient use of space. The larva of both mealworm and BSF are kept in crates, from which they are not able to crawl out. This allows for crates containing larva and the material which they are feeding on to be stacked vertically, so long as there is enough space between the containers to allow for air circulation. An example of stacking of containers containing mealworm larvae is shown in figure 2.8. This means that one room can contain large amounts of insects, and the high energy consumption can possibly be partially compensated for by the high yield. By careful design of the production facilities, one can also take advantage of the metabolic heat produced by the insects as they feed, further increasing the efficiency of the system by lowering the external heating demand (Oonincx and De Boer, 2012).

Design of facilities

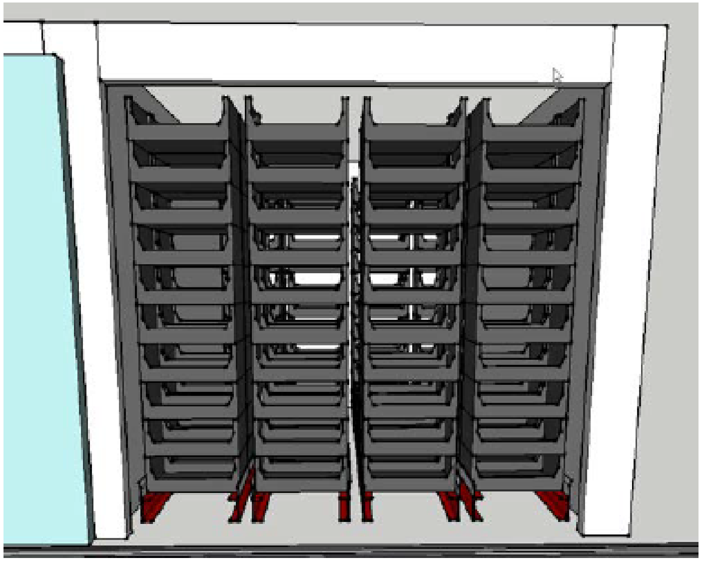
The implementation of this vertical farming principle can be done using various designs. The containers can be organized in racks as shown in figure 2.8, which allows for great flexibility through manual moving and feeding of the racks. Other systems are increasing the use of automated

Figure 2.8: An example of stacked containers containing mealworm larva, courtesy of Invertapro.

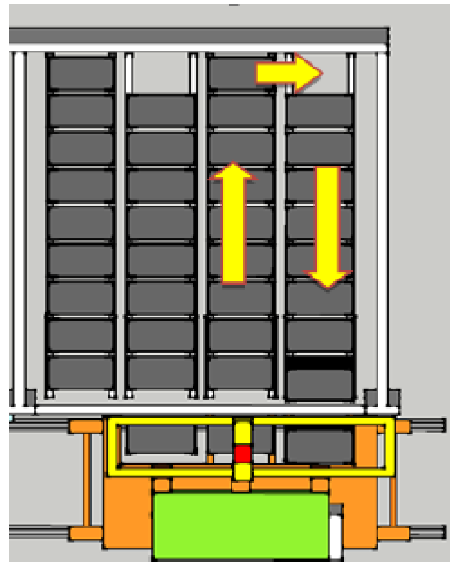
technology, to reduce costs and increase efficiency and accuracy of the systems. Some examples of possible facility designs will be presented here.

Cell-based system developed by Vives, Sirris and Inagro One example is the automated feeding system developed by the research institutions Vives, Sirris and Inagro in Belgium. After careful tracking of time spent on different activities in the production of yellow mealworms, they found that the feeding process was the most time-consuming, and thus also most costly step of the production, comprising 70 % of the total production costs (Schillewaert et al., 2016; Coudron, 2019). In collaboration, these research institutes developed a modular system based on cultivation cells with an automated robot feeding system for wet substrate, as shown in figure 2.9.

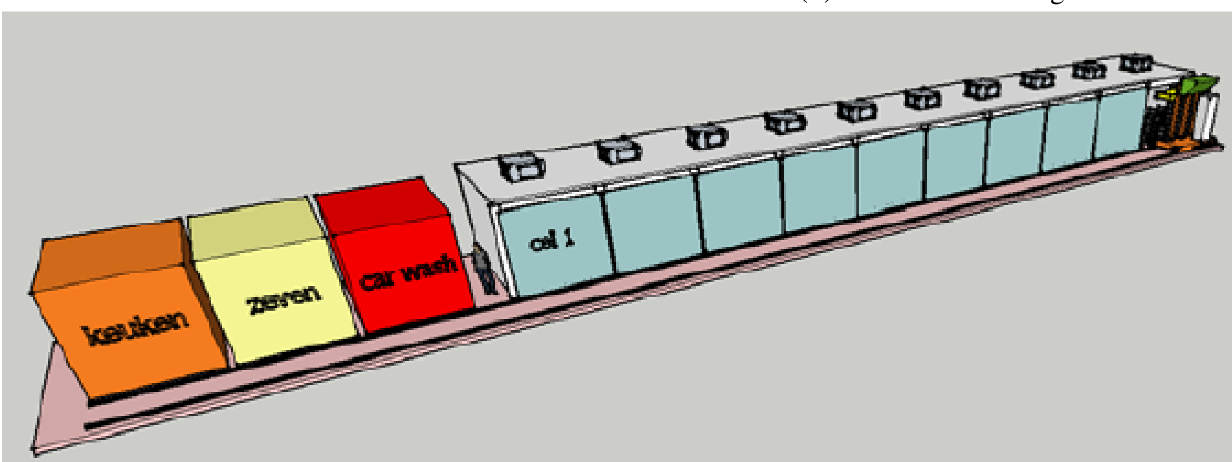
Cells containing a set number of mealworm crates, as shown in figure 2.9a, are placed alongside each other, with an automated feeding robot stopping outside each cell to feed all the crates inside each cell, as shown in figure 2.9c. This is accomplished by a roller mechanism on the feeding robot, which pulls one stack of crates onto the feeding machine as shown in figure 2.9b. The feeding robot is loaded with feed, and distributes a given amount to each crate through a moving arm with a spray nozzle. When all crates in one stack is fed, the stack is placed back into the cell, while another is pulled onto the feeding robot. This way, all crates are efficiently provided with an exact amount of feed in relatively short time. This system is modular, and can be expanded with more cells to increase production volumes. It can also be supplemented by other cells performing other production steps, such as possibly pre-treatment of feeding substrate, sieving mealworms from their excreta or final harvest of larvae. The cells can also be stacked on top of each other, allowing for more efficient use of area. According to Coudron, by having a limited number of crates in separate closed spaces, risk of disease is reduced, as a limited amount of larva share the same space, and can easily be isolated in case of disease outbreak. Environmental conditions in



(a) One single cell for insect production.



(b) Automated feeding robot for modular cells

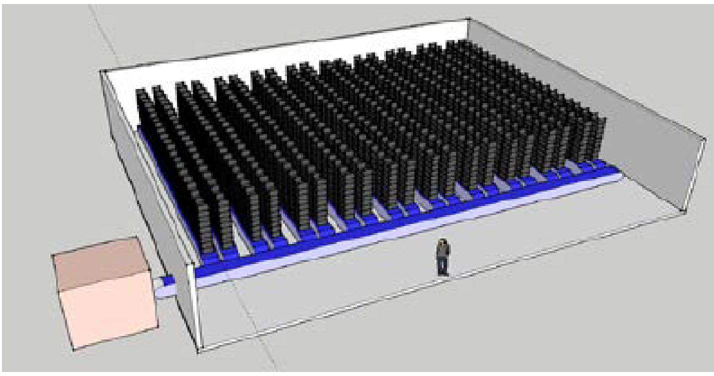


(c) Modular automated feeding system for yellow mealworm production.

Figure 2.9: Modular insect production system for yellow mealworms with robot for automated feeding of all crates in each cell, courtesy of Inagro, Sirris and Vives, Belgium.

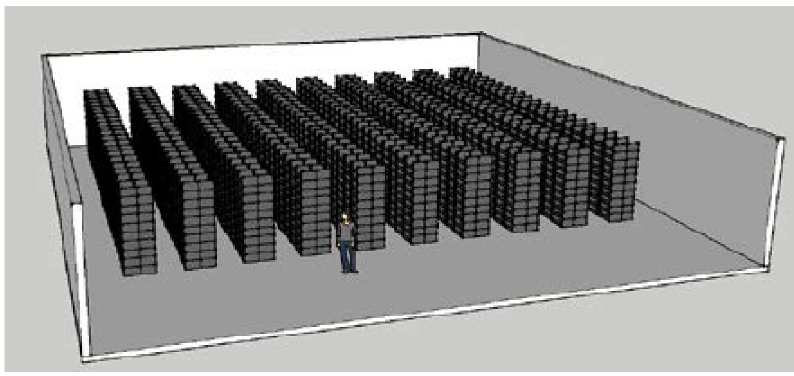
each cell can also be easily monitored and adapted to the life stage of the mealworms contained in each cell.

This design was chosen after an extensive process, considering both a continuous system and batch-wise production. Other configurations than the modular system was also investigated, including a static container stacking principle, fed either by a central feeding network, as shown in figure 2.10a, by use of a mobile feeding robot, as shown in figure 2.10b or by a feeding network with one feed point for each crate, as shown in figure 2.10c. These options did however present significant challenges, such as expensive investments for the central feeding network system, the need for complex programming for the mobile feeder robot and the possibility of clogging in the feeding network with separate feeding points (Schillewaert et al., 2016).



(a) Static container system using a central feeding network.

(b) Mobile feeding robot for feeding of a static container system.

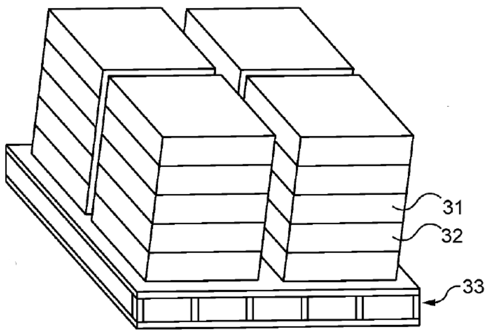


(c) Static container system using a network of feeding points.

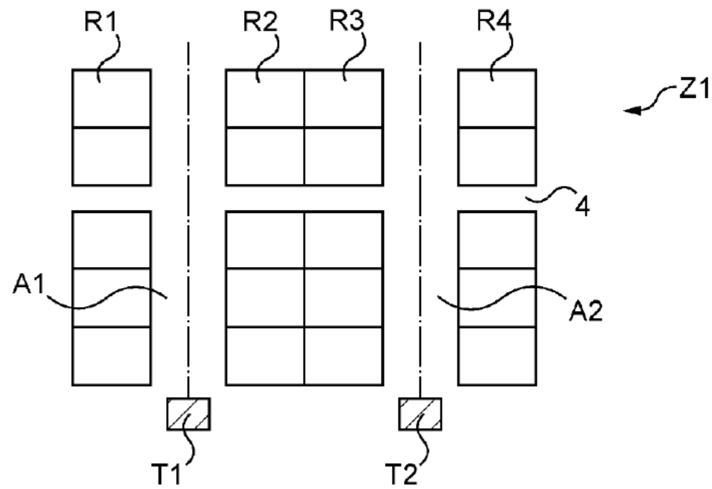
Figure 2.10: Different options for automated feeding of a static system of crates, as investigated by Inagro, Sirris and Vives, Belgium (Schillewaert et al., 2016).

Automated farm for rearing insects by Ynsect A different system to those presented above has been patented by Ynsect (Comparat et al., 2018). The farm structure suggested in this patent is primarily divided into two zones, one zone comprising the crates of insects, and another zone for rearing-related operations such as feeding and sieving out the insect excreta. In this system, bioconversion takes place in crates, which are stacked in so-called "basic units" comprising one loading pallet, for example of the type "Europe pallet". Depending on the size of the pallet there are different stacking possibilities, but taking the Europe pallet as an example, this could serve as a base for 4 containers, as shown in figure 2.11a. The number 33 in the figure refers to the pallet, while number 31 and 32 are single crates. As shown, the crates are stacked on top of each other to create a column and thus efficiently uses the floor area. There are many possible configurations of pallets and crates stacked on each pallet. The pallets are further organized in racks, which are serviced by an automated storage/retrieval machine. The storage/retrieval machine can collect a pallet, and transport it to the second zone, or to another place inside the first zone.

An example of how racks can be organized is shown in figure 2.11b. Here, each of the numbered R's refers to a rack, comprising stacked pallets ("basic units"), which contains several columns of stacked crates. Z1 refers to zone one and T1 and T2 are storage/retrieval machines, servicing separate aisles, A1 and A2. The number 4 represents an air curtain, used to separate the racks into smaller zones within the first zone. This separation allows for sorting the racks by for example life stage and development, thereby providing the opportunity to control environmental conditions and



(a) Stacking of crates on a pallet.



(b) Organization of racks, each rack consisting of stacked pallets.

Figure 2.11: Possible organization of crates onto pallets to make racks, as proposed by the patent by Ynsect (Comparat et al., 2018).

disease outbreaks specifically for different development stages of the species being farmed. This system also operates with an automated feeding system, but in place of a static configuration of crate, each pallet is collected by a storage/retrieval machine and sent to another zone for feeding. The second zone is in the patent organized as a series of stations, each station performing a different operation. Pallets from the first zone is transferred to the second zone via an interface connected to a conveyor belt, and can be returned to the first zone via the conveyor belt after for example having been fed.

Robot for feeding and de-palletising crates by RFA Rijlaarsdam Factory Automation B.V. Yet another system, focusing on automated feeding, has been developed by the company RFA Rijlaarsdam Factory Automation B.V. in the Netherlands. This system utilizes a six axis robot arm which is equipped with a clamp gripper to lift two crates at a time. This allows for the two crates to be lifted, i.e. de-palletised, after which they can be moved to a point of interest within the operational radius of the robot arm. The purpose of this de-palletising, as designed for the original use of the system, is feeding of the yellow mealworm larvae by moving the crates under a mounted feed dosing unit, after which the crates are palletising again.

The use of the robot arm also allows for de-palletised crates to be emptied into a screening machine, preforming the separation of the insect excreta from the live larvae which is needed at regular intervals to ensure optimal growth and prevent disease outbreaks. After the contents of the crates have been emptied into the screening machine, the robot arm is designed to move the crates onto a conveyor belt which transports the crates through a washing tunnel. When the crates have been cleaned, the robot palletises the crates again, which allows for a new cycle of mealworms to be reared. The crates are presented to the robot by way of a ground-based conveyor system. This robot system is shown in figure 2.12, including the blue crates in which the mealworms are kept, and the ground-based conveyor system for transporting the crates to the robot for handling. Figure

2.12a shows the robot arm about to de-palletise two crates, figure 2.12b shows the robot holding the two de-palletised crates to the feed dosing unit mounted from the ceiling and figure 2.12c shows the robot arm in the process of lifting two de-palletised crates.

(a) De-palletising of crates.

(b) Feeding crates from a ceiling-mounted dosing unit.

(c) Lifting of crates.

Figure 2.12: Robot system for feeding and de-palletising of crates containing yellow mealworms, courtesy of RFA Rijlaarsdam Factory Automation B.V. (Rijlaarsdam, 2019).

2.5.6 Harvest and slaughter

When the larvae are fully grown they are harvested. Harvesting is usually performed by a final sorting of larva from frass and any remaining feed residues using some form of screening/sieving process (IPIFF, 2019). This process can be automated, semi-automated or rely on manual labor, depending on the level of automation in each facility. This sieving process will generally resemble the sieving process described for the separation of yellow mealworm larva from their frass during bioconversion, and might consist of several consecutive sieves of different mesh sizes (Ortiz et al., 2016; Comparat et al., 2018).

According to the previously mentioned guidelines made by IPIFF, some pre-treatment steps are often taken before euthanizing the insect. Some insect species, like the yellow mealworm, is left in trays without feeding substrate for 12 - 24 hours after harvest, to allow the larvae to empty their guts before being euthanized. Some insect producers also operate with a cleaning step, where the insects are rinsed in tap water to ensure hygienic processing. It is also common to keep harvested insects in cold storage prior to slaughter, to immobilize the insects. This simplifies transport of the insects, for example if they are to be processed at another facility, and also provides some buffer capacity before further processing. However, Wynants et al. (2017) found that starvation and rinsing of yellow mealworm larvae after harvest did not have any effect on the microbiological quality of the larvae.

Independent of these pre-treatment steps, the insects must be euthanized at some point. There is currently no standardized procedure for this process, but killing by hot water, i.e. blanching, or freezing is common (IPIFF, 2019). Different euthanizing methods will necessarily have an impact on the total use of resources such as energy, water and land. The method used will also affect the safety with respect to microbiological hazards and shelf life of insect products. The importance of using some kind of hygienization procedure such as sterilization, pasteurization, blanching or roasting before consumption of edible insects is highlighted by both European Food Safety Authority (2015) and Megido et al. (2017).

2.5.7 Post-processing of products

When the insects have been euthanized there are many different options for further processing the harvested larvae into marketable products. According to IPIFF, common processing methods include the removal of water using either freeze drying or microwave-drying, grinding to obtain a fine powder and fractioning to separate the lipid fraction (fat) from the protein fraction into oil and meal, respectively. Freeze drying is used to ensure high quality products by preserving parameters such as texture, color, aroma and nutritive value, which is particularly important if insects are to be sold whole for human consumption (Kröncke et al., 2018).

However, this kind of processing is both expensive and energy intensive, and other methods such as microwave drying, fluidized bed drying and drying with vacuum for heat-treating mealworms have been investigated with good results (Lenaerts et al., 2018; Kröncke et al., 2018). The effect of different post-processing methods, in combination with specific slaughtering methods have received attention in the last few years, particularly with respect to quality and microbiological safety of end products. Melis et al. (2018) investigated the effect of freezing and drying on the yellow mealworm, and found a negative effect on the product quality if the insects are subject to drying for a long time at low temperature. Freezing followed by drying at high temperature for a short period time did however not have significant impact on the quality.

As the yellow mealworm is farmed for human consumption to a larger extent than for example the BSF, most research presently available focus on the processing properties of the mealworm. With increasing production of insects for both food and feed purposes, more research on optimal processing technology can be expected. Different equipment and different combinations of processing methods are used by European insect producers today, depending on the insect species produced, regulatory requirement in the country of production and the intended market for the products.

2.6 Food and feed safety

Insects represents a relatively new food and feed commodity in Europe, and special care is therefore used with regards to the safety of consuming insect-derived products for humans and animals alike. Based on the cautionary principle, the laws and regulations currently applicable to insects intended for food and feed purposes is quite strict. The European Union is regulating insect production through laws which provides requirements to be fulfilled by insect producers wishing to commercialize their products. This strict legal framework which European insect producers must adhere to is noted as one of the largest barriers to fast up-scaling of insect production todayIPIFF (2018).

By definition, insects are a type of livestock as per European legislation, and the producers of insects must thus adhere to legislation pertaining to the production of other livestock. This is an important point to keep in mind, as the insect industry is relatively new, and laws currently applying to insect production were not written with the specific insect production in mind. These laws are thus based on adaptions made to existing laws regulating other types of livestock production, which implies that no special considerations are made for the characteristics which separates insects from other livestock.

The most drastic result of this is the restrictions pertaining to which types of feeding materials are allowed for insects. As a production animal, an insect can only be fed plant-based materials, which effectively excludes feeding materials such as manure, food waste and other waste streams (European Commission, 2011). Though this might seem excessive as many insect species, such as the BSF, have been shown to thrive on exactly these feeding substrates, these restrictions are implemented to prevent the spread of transmittable spongiform encephalopathies (TSEs). This disease is a serious risk for human and animal health alike, as it causes degeneration of the brain tissue which is fatal to animals and very severe to humans (EU, 2001). The disease is connected to prions in animal proteins, and only some animal products are thus accepted as feed, including eggs, milk, honey, bloodmeal from non-ruminants, fishmeal and rendered fat (European Commission, 2011).

Based on the same concerns for TSEs, which animals are allowed to be fed with insects is also strictly regulated. As of today, only pets, furred animals and animals used in aquaculture are allowed to be fed with insects, in the form of process animal protein (PAP) (EU, 2001). However, IPIFF has informed that insects as feed for poultry and pigs are being considered by the European Commission at this time, which could potentially increase the possible markets for insect-derived products (IPIFF, n.d.). Currently allowed uses of feedstuffs of animal origin are summarized in table 2.3, adapted from Fischer et al. (2018). Insects are outlined in red in the table, and the table should further be interpreted as the boxes which are red and marked with representing a combination of a feedstuff for an animal which is not allowed, and the green boxes marked with Vs show combinations of feedstuffs and animals which are allowed to eat this feedstuff.

Norway is not a member of the European Union, but as a member of the European Economic Area, the regulatory frameworks applicable in Norway are often similar to those in the European Union. This applies for the laws and regulations pertaining to insects, and the regulatory landscape which is applicable for Norwegian insect producers is thus much the same as for other European producers. Though the strict adherence to the precautionary principle is reasonable to prevent damage to human and animal health, it is clear that this regulatory framework is limiting the growth

Table 2.3: Overview over feedstuffs of animal origin and allowed application in feed for different animals, adapted from Fischer et al. (2018).

Feedstuffs of animal origin	Ruminants	Insects	Aquaculture	Pets	Furred animals	All other farmed animals
PAP from ruminants	X	X	X	V	V	X
Blood products of ruminants	X	X	X	V	V	X
Hydrolized protein of ruminants, except skins and hides	X	X	X	V	V	X
Collagen and gelatine of ruminants	X	X	X	V	V	X
PAP from non-ruminants (not insect- or fishmeal)	X	X	V	V	V	X
Fishmeal (PAP)	X	V	V	V	V	V
PAP of insects	**X**	**X**	**V**	**V**	**V**	**X**
Blood products from non-ruminants	X	V	V	V	V	V
Dicalciumphosphate and tricalciumphosphate	X	V	V	V	V	V
Hydrolized protein of non-ruminants, including skins and hides	V	V	V	V	V	V
Collagen and gelatine of non-ruminants	V	V	V	V	V	V
Eggs and products of egg, milk, diary products, foremilk (colostrum)	V	V	V	V	V	V
Rendered fat	V	V	V	V	V	V
Kitchen- and food waste	X	X	X	X	V	X
Solid municipal waste	X	X	X	X	X	X

of the insect industry.

The ban on using organic waste streams such as food waste from kitchens and households as well as manure is especially restrictive, as these are some of the most abundant feeding substrates available which also holds the potential to significantly lower the environmental impacts associated with insect production. As of now, insect producers in Europe, including Norway, are limited to using pre-consumer waste streams which are fully traceable and clean. However, regulatory changes are expected as insect production systems are better understood and documented through research.

Chapter 3

Methodology

In this work, the potential of insect production as a sustainable waste management and protein production technology in Norway is to be investigated. To enable assessment of the environmental performance of such a system, the LCA framework, as described in section 2.1, was chosen as the assessment tool. LCA was chosen because it is recognized as one of the most complete methods for assessing environmental impacts for the full life cycle of products and services alike, and is commonly used as the method of choice for food products and supply chains (Halloran et al., 2016). The LCA performed in this study conforms to the LCA procedure specified in the ISO standard and described in section 2.1 (ISO, 2006). The four main steps of LCA will be presented as follows: the goal and scope of the study has already been briefly stated in section 1.2, but will be further discussed in this chapter. The life cycle inventory will also be described in this chapter, divided into a general inventory for an insect production facility in section 3.2 and a case-specific inventory for insect production in Western Norway based on Norwegian resources in section 3.3. The life cycle impact assessment will follow in chapter 4 with a consecutive sensitivity analysis in chapter 5. The interpretation of the results will be presented in chapter 6.

3.1 Goal and scope of this study

3.1.1 Goal

As stated in the introduction, the main purpose of this study is to preform an environmental impact assessment of an industrial-sized insect production system in Norway. The goal is that this study can provide a reference for the environmental impact pathways for such systems as the insect industry takes its place within the Norwegian circular economy. This study will as such be a supplement to ongoing research activities such as Entofôr, which aims at developing tools to help grow the insect production sector in Norway. This study will be of particular interest for commercial actors such as the Norwegian insect production company Invertapro and their waste management partner BIR, as they are now in the process of scaling up insect production in the Western region of Norway.

In this study, particular attention was paid to the production processes which are needed to produce insects. This is of interest when new production practises are to be established, as is the case with insect production in Norway. Recent studies on the environmental impacts of existing operational insect production factories in Europe have emphasized the high impact associated with the feeding substrate provided for the insects and the energy sources used to provide heat and electricity to the system (Oonincx and De Boer, 2012; Thévenot et al., 2018; Smetana et al., 2019). This prompted an investigation of how the use of Norwegian resources would affect these parameters. A sensitivity analysis is therefore performed for different feed and energy scenarios to explore the impact on the total environmental performance of the system. To fully understand the extent of the environmental impacts of the system, this system will be compared to other systems providing the same functionality in terms of protein production. This allows for an interpretation of how large-scale insect production facilities can interact with already existing technologies and markets and potentially improve the environmental impact of the food chain as a whole.

3.1.2 Scope

The production system

In Norway there are only seven insect species which are currently allowed for production for use in feed (Mattilsynet, 2017). For use in food, there are even fewer species allowed, pending approval as novel food in the EU (Mattilsynet, 2016). Based on this, there are only a few insect species which are eligible for production in Norway at this time. Invertapro is a Norwegian insect production company located in Voss, which has started small-scale production of the yellow mealworm for human consumption. They are planning on scaling up production of this species in addition to starting up with another species, namely the black soldier fly, to provide as a feed ingredient for use in Norwegian aquaculture. By producing two species with different characteristics, Invertapro is building a very flexible system, equipping themselves for serving multiple markets (Ringheim, 2019).

As described in section 2.4, the yellow mealworm and the BSF prefer different feeds, which makes them suitable for handling different types of organic side- and waste streams. Producing both species at the same time thus allows the system as a whole to absorb a large variety of different organic materials, ranging from completely dry residues from the milling and bakery industries to for example wet food waste from breweries or fruit and vegetable processing. The two species are also suited for different end uses; where the yellow mealworm has been reared both for food and feed purposes, BSF is mainly reared for use in feed. Joint production of the two species therefor enables the producer to serve both the feed market and the human food market, and was therefore modelled in this study.

To further maximize the flexibility of this combined system, it was decided to model a production system in which the two species are farmed at the same location, but in separate facilities. This reduces the risk of sickness wiping out the whole population, and ensures continued production even if one species should fall victim to circumstances demanding the complete sanitation of that colony. It also enables easier compliance with regulations pertaining to hygienic operation of insect production facilities, particularly by lowering the risk of cross-contamination (IPIFF, 2019).

System boundary

To properly define the scope of this study, the system boundaries of the modelled system must be established. One of the most pertinent questions in this regard is what product or services the edible insects produced in this system aims at replacing or competing with. As the market for insects, both for food and feed purposes, is not well established in Norway yet, this study aims at comparing insect products to products which they might be competing with or replacing in the future. This is implemented in the study by applying a system boundary that does not include avoided products from other systems. This corresponds to the aim of this study, which is only to provide a foundation for comparison on a general basis, without dependency on the development of the market, i.e. which specific products insects can replace in terms of food and feed products. This allows for the comparison of for example insect meal to both soybean meal and fish meal, without locking the system into replacing either one alternative specifically. This approach is chosen to fully reflect the potential of the insect industry in Norway, without predetermining the conditions for how this potential can be achieved. This also aligns well with the research questions defined in this study, in which the focus on the processing processes internally in the system was established.

This is particularly important with respect to the use of the fertilizer product represented by the insect excreta. In the study by Salomone et al. (2016), the frass fertilizer from the insect production system was assumed to replace nitrogen fertilizer, i.e. the system boundary of the system was extended to include the replacement of mineral fertilizer with insect frass. This significantly lowered the environmental impacts from the system as a whole. However, Hanserud et al. (2018) emphasised that the benefits of nutrient recycling is often overestimated when extending system boundaries to include avoided use and production of mineral fertilizers in LCAs. The primary cause for this is that conventional fertilizers are often replaced on a one-to-one basis with other fertilizer products, eg. one kg insect fertilizer is assumed to replace one kg mineral fertilizer. This approach does not take the actual nutritional qualities of the two fertilizer products into consideration, particularly in reference to the actual soil nutrient requirements by the soil on which the fertilizer is applied. The assumption that the system boundary can be be extended so that the production of one kg of one type of fertilizer means the avoided production of one kg of another type of fertilizer can thus cause significant uncertainty in a study.

This motivated a gate-to-gate modelling approach in this study, meaning no system boundary extension to include avoided products. With reference to the fertilizer example above, the choice to not include avoided products in this study is considered to be a robust modeling choice. The production system, for both species follows a general production cycle from gate to gate as shown in figure 2.4. The system follows the processes described in sections 2.5.3 through 2.5.7, and includes pre-processing of feedstock, reproduction, bioconversion, harvesting, slaughter and post-processing into products. The production of the two species produces different products. The yellow mealworm production system is modelled to produce whole, dried larvae, organic fertilizer, meal and oil. The BSF production results in meal, oil, puree and organic fertilizer. In total, eight marketable products are produced from the whole production system.

Functional unit

Ideally, an insect production facility is built with the intention of upcycling organic waste streams into protein-rich food and feed. Such a system produces protein based on recycled nutrients, thereby also providing a waste management service. However, a limitation of LCA studies is that a system can essentially only be studied with regards to one functionality at a time. Thus, a choice of the primary functionality of the system must be performed to facilitate an LCA in this study. Technically, both functionalities, i.e. protein production and waste management, could be included by applying an industrial ecology approach as suggested by Halloran et al. (2016). To enable this form of system-expansion, efforts would have to be made to create models and accompanying inventories for comparable waste management options such as composting, anaerobic digestion or incineration. However, given the time limitations and the goal set for this study, this was considered to be too time-consuming and outside the scope.

In addition to the modeling challenges associated with this form of system expansion, the regulations governing insect production also limits the usefulness of this approach. Considering the regulatory landscape of today, as described in section 2.6, using insects for waste management of large organic waste flows such as municipal household waste and restaurant waste is not eligible right now, though it might be relevant in the future. The same regulations have however already opened up for the use of insects as feed for use in aquaculture, and the demand for this new feed ingredient is surging (Skretting, 2018). Additionally, several Norwegian businesses have started producing insects for human consumption, which has been met with curiosity and interest by the public (Ringheim, 2019). These considerations motivated the choice of protein production as the main functionality in this study.

In addition to protein, an organic fertilizer is produced from the insect excreta, both from the yellow mealworm and from the BSF which can be used as a fertilizer on farmland (Thévenot et al., 2018; Salomone et al., 2016). From the production of meal, an oil rich in fat is also produced, both when mealworm larvae and BSF larvae are processed into meal. This oil can be used as a feed additive for livestock, and has been suggested as a sustainable alternative to palm oil in broiler chicken diets (Benzertiha et al., 2019). From the processing of BSF into meal, there is also a puree by-product which has similar qualities to for example chicken meat (Smetana et al., 2019). This implies a great diversity in functionality, and thus presents many possible functional units for this system, even if it has been limited to mainly focus on protein production.

To fully reflect the multi-functionality of this system, a **functional unit of 1 kg of product** is used in this study. This allows for the system to be analysed with respect to the different output products, and does not make the results dependent on a given characteristic of the products or their intended end use. Other studies have used for example 1 kg of edible protein, but this creates a dependency on the protein content of a given product, which is further dependant on the feeding substrate provided for the insects.

As will be discussed in more detail in section 3.3.1, the feeding material assumed as input to the system modelled in this study is based on theoretically calculated available amounts of different feeding material in the Western region of Norway. These materials are appropriate feeding materials for insects, but have not been tested in commercial production, and no information on the final nutritional composition of insects fed with these materials are available at this time. Using a functional unit based on nutritional parameters such as protein or lipids is thus considered to present a significant uncertainty, and this approach was therefore not used in this study.

Due to a lack of data and information of the performance of insect frass as fertilizer, it was chosen not to focus on this by-product in this study. No publicly available scientific literature exists as of today on the effects of insect fertilizer on either on plant growth nor emissions from its application on farmland. Many European insect producers have launched insect fertilizer products on the market, but as there currently exists no scientific documentation for these products, it would be difficult to model in this study. However, many insect producers are working on documenting the properties of these fertilizer products at this time, and there will most likely be more focus on this by-product in the future.

Type of LCA and allocation procedures

LCAs can be divided into two sub-groups, attributional LCAs or consequential LCAs, depending on what the aim of the LCA is. This study aims at describing the physical flows which are of relevance for the life cycle of insect production and associated subsystems, which led to the use of the **attributional approach** to the life cycle inventory in this study, adhering to definitions presented in Ekvall et al. (2016). Following up on this choice, care must be exercised when modeling the system to assure the application of consistent and appropriate allocation rules.

The LCA performed in this study follows the ISO standards for LCAs (ISO 14040, 2006; ISO 14044, 2006). SimaPro v8.5.2. software (PRé Consultants B.V.) implementing the Ecoinvent 3.1 and Agri-Footprint v.2.0 databases for background data (electricity production, heat generation, water supply and feeding substrate components) was used for the life cycle assessment impact modelling. Allocation procedure must be chosen when using the Ecoinvent and Agri-footprint databases in Simapro. Allocation, cut-off by classification is recommended by Ecoinvent for new practitioners, which fits well with the status of this study as a master thesis and thus also a learning process (Ecoinvent, n.d.). Additionally, allocation at the point of substitution, which is the default allocation method in Ecoinvent is very complex and has been known to produce strange results in some cases, which further promotes the cut-off approach as a reasonable choice (Ponsioen, n.d.). Based on these considerations, the cut-off by classification - unit allocation method for the use of Ecoinvent in SimaPro was chosen.

Similar to Ecoinvent, allocation procedure must be chosen for the use of Agri-footprint in SimaPro. Agri-footprint is used to obtain background data for the feeding substrate, and contains three possible allocation methods, namely mass allocation, energy allocation and economic allocation (BV, 2015). All three allocation methods could in theory be used in this study, as they all value important attributes of the feed material in the context of insect production. Stable (mass) quantities of feed is necessary to ensure continuous, predictable production of insects, and mass allocation could therefore be an appropriate method. From another point of view it can be said that it is the energy content in the feed in terms of protein, fat and carbohydrates that provides the foundation for the production of protein and fat-rich products from the process. Then again, the economic value of the different feed materials varies greatly, and from the producers point of view, this is a crucial factor when determining what should be included in the feed mix.

To represent the insect industry as it is today as accurately as possible, economic allocation was chosen for this study. Ideally, insect producers would use only non-utilized organic waste streams as feed material for their insects, so that their production would not be at the expense of other uses of for example feed materials. However, this is not the situation today, both for regulatory and practical reasons. Economic factors will therefore most likely largely determine which ingredients are used until the insect industry has fully established its value chains and optimized its production processes. Economic allocation in Agri-footprint is therefore chosen in this study as allocation method for upstream impacts from feeding substrate. Using economic allocation for upstream impacts also enables comparison to other studies of insect production systems, in which economic allocation is the most used allocation method.

Economic allocation was also chosen for assigning the relative percentage of impact to the different by-products from the system. This is practised in most other available LCAs of insect production systems as well. However, large differences exists as to the final allocation factors used, depending on where the data is acquired and what products are studied. Some allocate environmental burdens between meal and fertilizer (Salomone et al. (2016)), while others allocate between meal and oil (Thévenot et al. (2018)) while others again operate with more products (Smetana et al. (2019)). Salomone et al. (2016) reported an economic value of 995 $ per ton for BSF meal and 5 - 10 $ per ton for fertilizer. Thévenot et al. (2018) reported that 88.5 % of the total environmental burden of mealworm production was allocated to meal, with the remaining 11.5 % allocated to oil.

There are in total eight products from this system, of which the protein products (meal and whole, dried larvae) are the main products. Additionally, fat-rich oil, puree and fertilizer is produced and are defined as the by-products of the system. For this study, allocation was performed based on projections from Invertapro with regards to the production of yellow mealworm. Meal and oil are assumed to be equally priced, while whole, dried larvae are assumed to have a sales value of twice the amount of meal. Fertilizer is assumed to be to sold at a price approximately of approximately 1/25 of meal and oil, and is thus not allocated any burden in this study, as its value is so low compared to the other products. Attributing equal environmental burden to meal and oil will likely cause significantly lower impact for meal compared to other studies, as meal is commonly attributed most of the burden alone in other studies.

With regard to the production of BSF, the production technology modelled in this study is based on Smetana et al. (2019), and therefore it would be most appropriate to to use allocation factors from this study for the BSF end products. However, such factors were not possible to attain, except from an implication that meal is valued four times higher than oil, which again is valued higher than fertilizer. No indication was given for the economic value of the puree. No other existing study includes the production of puree from BSF nor any other insect species. Based on these indications, and with the values reported by Salomone et al. (2016) and Thévenot et al. (2018) in mind, economic allocation was performed according to the following allocation rules for BSF products in this study: 70 % of total burden allocated to meal, 17.5 % to oil and 12.5 % to puree. As previously mentioned, the fertilizer products are not a focus of this study, and as this product has limited economic value, no burden was allocated to the fertilizer. The allocation factors used in this study are summarized in table 3.1.

Methodology of impact assessment and impact categories

This study can be divided into four main parts: 1) foreground modelling of industrial-scale production of yellow mealworm and BSF, 2) attributional background LCA modelling and allocation of impacts to by-products, 3) comparison of the products from this system with similar products and 4) sensitivity analysis of parameters identified as impact hotspots. To facilitate the modeling and comparison, a specific method for impact assessment must be chosen. As observed in section 2.3, the methods used in other studies of insect production systems varies largely, though CML, ReCiPe and IMPACT 2002+ seem to be the most frequently used.

The methodology chosen should facilitate an evaluation of relevant impact categories with

Table 3.1: Economic allocation of total environmental impacts between end products

Insect species	End product	Economic allocation	Source
Yellow mealworm	Meal	25%	Invertapro
	Oil	25 %	Invertapro
	Whole larvae	50%	Invertapro
	SUM	100%	
BSF	Meal	70 %	Miscellaneous
	Oil	17.5 %	Miscellaneous
	Puree	12.5 %	Miscellaneous
	SUM	100%	

respect to the defined goal and scope of the study. As an important part of the goal in this study is to compare the insect products from this system to other food and feed products, it is important to use a method which covers relevant impact categories from such production systems. Halloran et al. (2016) highlighted the importance of impact categories covering impact pathways such as climate change, resource consumption, nutrient enrichment potential, acidification potential, impacts on land use and water consumption. This aligns well with the impact categories exemplified in the FAO recommendations for environmental performance assessment of animal feed supply chains, namely climate change, fossil energy use, land occupation, eutrophication and acifidication (FAO, 2014a).

The ReCiPe method (Hierarchic perspective for Europe) offering eighteen different midpoint categories for assessment as indicators for the life cycle inventory results, was chosen for this study. Of these eighteen categories, the six most relevant categories were evaluated, based on the recommendations presented above: climate change [kg CO_2 eq.], freshwater eutrophication [kg P eq.], terrestrial acidification [kg SO_2 eq.], agricultural land use [m^2 arable] and water depletion [m^3]. In addition, energy use was evaluated using the Cumulative Energy Demand method v.1.09, presenting total energy use [MJ], as energy is stated to be of particular interest in this study.

Data sources and uncertainties

As previously mentioned, large-scale, automated operations are essential to realize the environmental sustainability potential of insect production (Halloran et al., 2016; IPIFF, 2018). Ideally, a life cycle inventory should be based on empirical data collected *in situ* to provide a realistic and accurate environmental impact assessment (Halloran et al., 2016). However, there is currently no existing large-scale insect production facilities in Norway which can serve as a model for such a system. Some entrepreneurs, like Invertapro, have begun producing insects in Norway, but so far only on a relatively small scale. It is therefore not possible to collect empirical data for industrial scale insect production based in Norway at this point.

Some companies in Europe, such as Ynsect in France and Protix in the Netherlands, are currently operating medium size production facilities with some implementations of automation, some also planning up-scaling in the imminent future. However, as this industry is experiencing large growth at the moment, producers are keeping their technologies and production parameters secret to keep their competitive edge in an exponentially growing market. Firsthand empirical data was thus no available.

The model used for insect production in this study is therefore based on a combination of different sources including a literature review and contact with insect producers and research facilities in both Norway and other European countries. Insight into considerations pertinent to Norwegian insect production was provided by Invertapro. Primary data on production technology for the yellow mealworm was acquired through a visit to Inagro's research facility in Belgium[1] and subsequent correspondence with Inagro's research partners, in addition to a literature review. This is considered to be acceptable in this study, as the aim is not necessarily to find an absolute answer, but rather to provide guidance to the emerging insect industry in Norway.

3.2 Life cycle inventory

The life cycle inventory for the production technology used for the two insect species will be presented in this section. This includes a detailed account of how the processing was modelled which results in two tables representing the production processes for each of insect species. The processes described here could in practise be implemented anywhere in the world with the access to the main input resources as defined in this section. The specific input resources used in this study, putting this system into a Norwegian context, is presented in section 3.3.

3.2.1 Production technology

As described in section 2.5, there are as of yet no existing process standard for which processing steps or technologies must be used for the safe production of insects for food and feed in Europe. Insect producers in Europe are using a variety of different methods, and it is difficult to predict which processing steps will be used in Norway and what level of automation will be achieved. Some choices and assumptions with regard to the production technologies used in a large-scale production facility for insects have therefore been made in this study.

Production capacity

The systems for production of the two species are modeled separately, but the production capacity has been defined for the system as a whole. The system is modelled to have a capacity for receiving 30 000 tons of organic material each year, based on estimations from Invertapro. Heckmann et al. (2019) suggested that an industrial level of insect production is achieved at a minimum of 1000 tons of biomass produced per year. The market for insects as food is currently smaller than the market for feed and the production of yellow mealworm was therefore modelled for the production of exactly this quantity, i.e. 1000 tons of live mealworms per year. The remaining incoming organic material was modelled as feed substrate for the BSF, facilitating a larger production of BSF than yellow mealworm. In reality, this would be a much more flexible system, depending on available residual raw materials in the area. However, for the sake of this study, a set distribution was set to facilitate the LCA.

[1]Inagro is an agency of the province of West Flanders in Belgium, working on agricultural research. Production of BSF and yellow mealworms is performed at laboratory scale to inform the development of the insect sector in this area. Visited on March 5th 2019. https://leden.inagro.be/inagro˙en/

Feed conversion ratios (FCRs), i.e. amount of feed substrate necessary for the production of kg live larvae, were obtained from literature to calculate the exact distribution of feed between the two insect species. Ideally, this should be based on FCRs calculated for the specific feeding substrate modelled in this study, but such data is not available at this time. Data from Oonincx and De Boer (2012) was therefore use instead, in which a production of 83 200 kg live larvae per year was reported, using 260 000 kg wet feed substrate per year and and 182 000 kg dry feed substrate per year. Dividing the total production of larvae by the dry feed substrate and wet feed substrate separately gives a FCR of 2.188 for the dry feed substrate and 3.125 for the wet feed substrate for the yellow mealworm. Multiplying the total production capacity of 1000 tons of live mealworms per year by the FCRs for dry and wet feed substrate gives a total feed substrate consumption by the mealworms of 5312.5 tons per year, including 2187.5 tons dry feed substrate and 3125 tons wet feed substrate.

No Norwegian insect producers currently farm the BSF, and the study by Smetana et al. (2019) was therefore used to find a representative FCR for the feeding substrate consumed by this species. The study by Smetana et al. reported a use of 32.24 kg feed substrate to produce 6.24 kg live larvae. Dividing the quantity of feed substrate by the quantity of live larva gives a FCR of 5.15 for BSF. Subtracting the feed provided for the mealworms from the total capacity of the system, i.e. 30 000 tons per year, gives a total of 24 687.5 tons feeding substrate for BSF per year. As described in section 2.4.2, the black soldier fly is more flexible with regards to its feeding substrate, and therefore does not require a separation between dry and wet feeding substrate.

The market for insects for human food is different to the feed market. The Norwegian aquaculture industry has stated their interest in insects as feed, and a quanta of 10 000 tons of meal per year has been suggested as a minimum production for insect meal to be a viable ingredient in feed formulations for the Norwegian aquaculture market (Gracey, 2019). However, producing this quantum from just one factory is unrealistic. Using the conversion rate of 32.24 kg feed substrate for a final yield of 1 kg meal from the BSF from the study by Smetana et al. (2019), a total of 322 400 tons of feeding substrate would be required to produce 10 000 tons of meal from the BSF per year. That is equal to 15.8 % of the total concentrate feed used in all of Norway in 2018 (Norwegian Agriculture Agency, n.d.[a]), or 1.5 times the total amount of organic waste collected from households in all of Norway in 2017 (Statistics Norway, 2018).

Collecting this quanta of organic material would require collection and transportation from all around Norway, which does not fit well with the goal of insect production as a *local* solution for waste management and protein production. Insect production should be established where there is access to both local resources as input to the system as well as a local market for the output from the system. It is therefore not assumed that the insect production system modelled in this study is able to supply the minimum quanta suggested by the Norwegian aquaculture feed market alone. The facility in this study is therefor modelled to be able to receive an amount of feeding material which can reasonably be expected to exist in close proximity to Bergen, i.e. 30 000 tons of organic material (Ringheim, 2019).

Black soldier fly production

Of the two species modeled in this study, the BSF requires the most complex production technology. As the adults can fly, special contraptions are needed for reproduction activities. The feeding substrate provided for BSF also has a high moisture content, further complicating rearing procedures. Without any special expertise withing the field of automation and mechanisation, it is difficult to imagine how this will be accomplished in large-scale production, and was thus found to be outside the scope of this study. No Norwegian insect producers currently farm this species. However, some European insect producers are farming the BSF, and have been working on automating and optimising this type of production for several years already. In a recent study, Smetana et al. (2019) used empirical data collected over nineteen months from the production facility for BSF operated by the dutch company Protix in Dongen in the Netherlands. The data-set in its entirety is protected by a non-disclosure agreement between the authors of the article and Protix, but a detailed inventory was provided in the article, disclosing process-specific parameters such as water consumption, electricity use and heating demand for central operations. The level of detail in the inventory is only found in one other study published to this day, namely the study by (Roffeis et al., 2017). However, this study is based on BSF production in West Africa, which presents entirely different terms for production than production in Europe.

The level of detail in the data presented by Smetana et al. was therefor determined to be sufficient to provide a model for BSF production in this study. The system is shown in figure 3.1, which is replicated from Smetana et al. (2019). From the figure it can be seen that the system boundary comprises the production facilities from the reception of feed material through all life stages of the BSF (egg, larvae, prepupae, pupae and adult) and final processing of the harvested larvae into marketable products. Transport of feed material to the facility and transport of the end products to consumers is outside the system boundary.

From figure 3.1 it can be seen that this system has four outputs, namely organic fertilizer, made from insect excreta and feed residues, fresh puree, lipids (fat) and protein concentrate in the form of meal. To produce 1 kg of insect meal, 6.26 kg of BSF larvae is needed. To feed these larva until they are ready to be harvested, 32.24 kg of feed is required. For each kg of meal produced, 3.82 kg of ready-for use fertilizer is also produced, in addition to 1.44 kg of insect puree and 0.34 kg insect lipids (oil). These ratios were used to calculate the necessary input of each of the parameters to the system based on the data provided by Smetana et al. The calculation steps can be found in appendix A.1.

The data presented in the study by Smetana et al. is thus used as inventory for the foreground processes in the BSF production system. This system is mainly divided into six production stages, namely feed handling, insect nursery, insect rearing and breeding, processing, product management and administrative areas support. In the original inventory, transportation of the feed to the BSF production facility was also included, but this has been excluded from the inventory presented here. Exclusion of transport activities will be further discussed in section 3.2.3.

The final inventory for the BSF production facilities can be seen in table 3.2, in which the values provided by in Smetana et al. (2019) is given in the column to the left, while the total input necessary to process the decided amount of 24 687.5 tons of feeding substrate per year by the BSF is given to the right. Note that heating has been converted from the unit of m^3 to kWh, by multiplying with the factor 10.395 kWh natural gas per m^3 natural gas. In addition to the described product outputs, wastewater is also an output of the system. Ideally, process-specific information on the production of wastewater should be obtained. However, this was not presented in the study by Smetana et al., but a total value of 227.72 L of wastewater produced from the whole system to facilitate the production of 1 kg of insect meal was reported, and is therefore used in this study as well. The total amount of wastewater produced per year is 174 374 612 L. The calculation for this

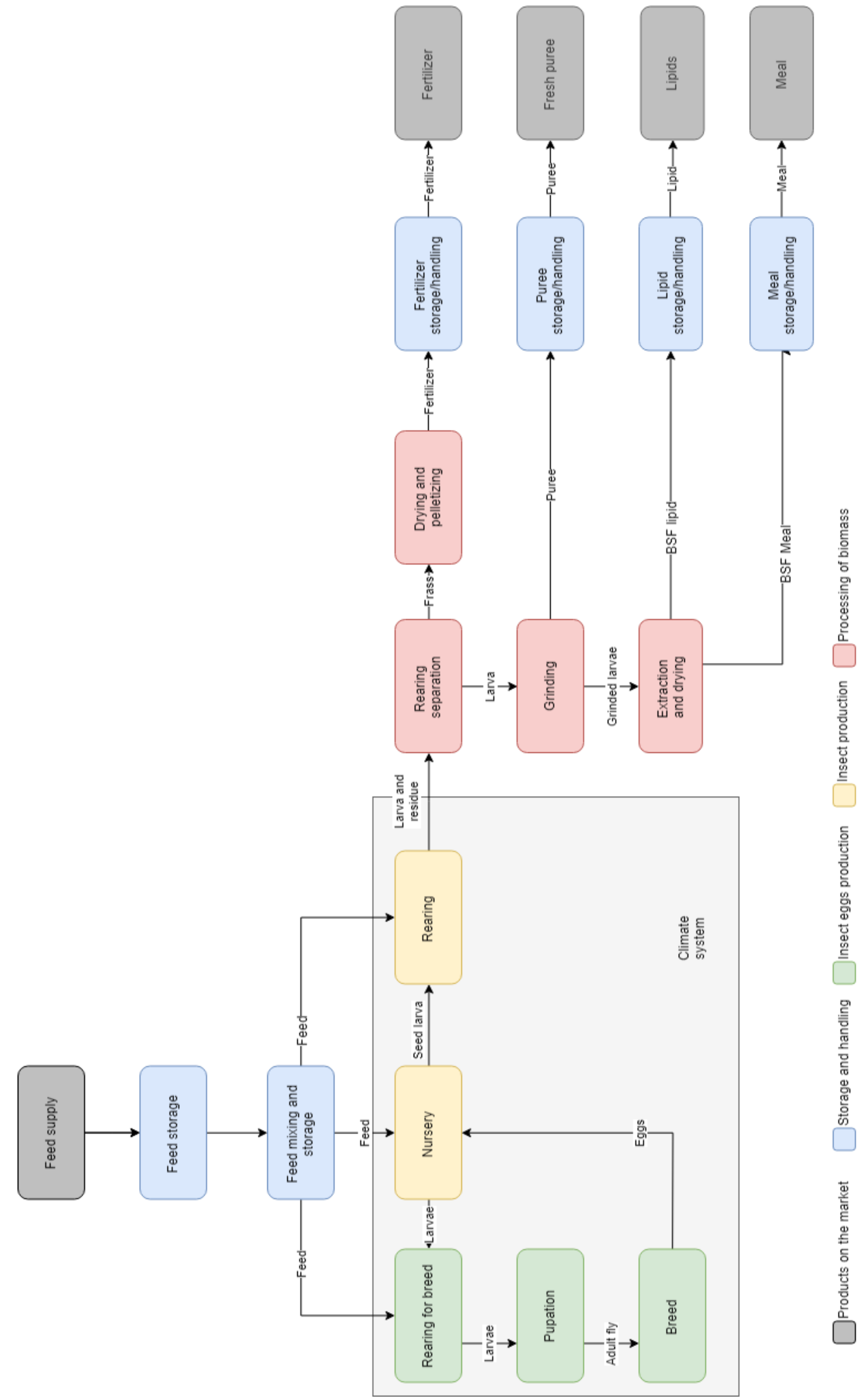


Figure 3.1: The model used for production of the black soldier fly in this study, adapted from Smetana et al. (2019).

value can be found in appendix A.3.2.

Feed handling In this stage feeding substrate for the BSF is received, after which it is mixed. This mixing assures that the feeding material achieves a homogeneous consistency, both with respect to moisture content and particle size. The BSF larvae prefer wet feeding substrate with a moisture content of 70 - 90 %, and water is therefore added in the mixing process. This pre-processing of feeding substrate is assumed to take place in a designated area, and comprises relatively large volumes of incoming feeding substrate. Transportation of the feeding material within the designated area is therefore included. The feeding material might have to be stored for some time as deliveries will not necessarily come every day, and storage of the feeding material is therefore included. Finally, cleaning procedures must be in place to ensure hygienic operation, including cleaning of crates and equipment which has been in contact feeding substrate.

Insect nursery In this stage the eggs produced by the adult flies are nursed into larvae. Each resource is therefore given in a unit per kg of eggs produced. This stage includes cleaning activities, encompassing all equipment and materials used, as well as the area in itself. The nursing area needs to be heated, as the BSF require high temperature and relative humidity to thrive and grow properly.

Heating is a crucial element in the production of insects, as both growth and reproduction rate is dependant on the environmental conditions. As stated in section 2.4.2, the BSF thrives best in a temperature range of 29 - 31 °C at 50 - 70 % relative humidity. However, how much heating is necessary to provide this warm indoor climate throughout the year depends on the outdoor temperature. Assuming that the heating demand will be similar for a BSF production facility located in the Netherlands and in Norway provides a big element of uncertainty, as the Norwegian climate is undeniably colder, on average, than the climate in the Netherlands. To adapt this inventory to Norwegian conditions, the concept of degree days was used to estimate the extra heating demand for BSF production in Norway compared to production in the Netherlands.

Degree days is a measure of how much and how long, in terms of temperature and days, the outside air temperature is below a certain level. The level is defined by the desired indoor temperature, i.e. the base temperature. In the article by Smetana et al. it is given that the data is collected from the Protix facility in Dongen, the Netherlands. The insect production modelled in this study is assumed to be established in Bergen, Norway (this will be discussed in more detail in section 3.3). The degree days for Dongen, the Netherlands and Bergen, Norway for a base temperature of 30 °C was collected from a database online (BizEE Software, n.d.). A total of 6859 degree days was obtained for Dongen and 7940 degree days was obtained for Bergen. The number of degree days for Bergen is as such 15 % higher than for Dongen, resulting in an assumption that 15 % more energy is needed for heating of the insect nursery facilities in this study than in the study by Smetana et al.

Insect rearing and breeding This stage includes both the larva stage and the adult fly stage. The adults mate in cages while the larvae are reared in plastic crates. The larvae do the job of digesting the incoming feeding material, and must thus be fed. Though it is not described in the research article by Smetana et al., it can be assumed that the feeding operating is automated. This means that the crates in which the BSF larvae are reared must be transported to a feeding station. This stage therefore includes both a feeding process and a transportation process, both of which are

Table 3.2: Inventory for BSF production facility, adapted from Smetana et al. (2019)

Production stage	Process	Resource	Amount	Unit	Amount for total production	Unit
Feed handling	Mixing	Electricity	0.0175	kwh/kg feed	432,031	kWh/year
	Mixing	Drinking water	0.0050	L/kg feed	123,438	L/year
	Transporting	Electricity	0.0050	kwh/kg feed	123,438	kWh/year
	Storing	Electricity	0.0025	kwh/kg feed	61,719	kWh/year
	Cleaning	Drinking water	0.6700	L/kg feed	16,540,625	L/year
Insect nursery	Egg production	Electricity	1524.6	kwh/kg eggs	1,282,146	kWh/year
	Heating	Heating	37.270	m3/kg eggs	374,682	kWh/year
	Cleaning	Drinking water	50.000	m3/kg eggs	42,048,602	L/year
Insect rearing and breeding	Feeding	Electricity	0.0200	kwh/kg fresh larvae	95,871	kWh/year
	Climate system	Electricity	0.4300	kwh/kg fresh larvae	2,061,222	kWh/year
	Transporting	Electricity	0.0120	kwh/kg fresh larvae	57,522	kWh/year
	Utilities	Electricity	0.1000	kwh/kg fresh larvae	479,354	kWh/year
	Heating	Heating	0.0600	m3/kg fresh larvae	3,438,191	kWh/year
	Cleaning	Drinking water	16.141	L/ kg fresh larvae	77,372,539	L/year
Processing	Insect separation	Electricity	0.0070	kwh/kg fresh larvae	33,555	kWh/year
	By-product separation	Electricity	0.0050	kwh/kg fresh larvae	23,968	kWh/year
	Grinding	Electricity	0.0090	kwh/kg fresh larvae	43,142	kWh/year
	Pelletizing	Electricity	0.0240	kwh/kg fresh larvae	115,045	kWh/year
	Extraction	Electricity	0.1390	kwh/kg fresh larvae	666,302	kWh/year
	Utilities	Electricity	0.0800	kwh/kg fresh larvae	383,483	kWh/year
	Cleaning	Drinking water	10.760	L/kg fresh larvae	51,578,497	L/year
	Drying	Heating	0.0400	m3/kg fresh larvae	1,993,154	kWh/year
Product management	Storage	Electricity	0.0760	kwh/kg of product	384,096	kWh/year
	Transporting	Electricity	0.0050	kwh/kg of product	25,269	kWh/year
	Utilities	Electricity	0.0340	kwh/kg of product	171,832	kWh/year
	Cleaning	Drinking water	2.6100	L/kg of product	13,190,660	L/year
	Heating	Heating	0.0200	m3/kg of product	1,407,944	kWh/year
Administrative areas support	Administration	Electricity	0.1300	kwh/kg fresh larvae	623,160	kWh/year
	Administration	Drinking water	1.8200	L/kg fresh larvae	8,724,244	L/year
	Administration	Heating	0.0042	m3/kg fresh larvae	281,772	kWh/year
			Totals	Electricity	7,063,156	kWh/year
				Drinking water	209,578,605	L/year
				Heating	7,495,744	kWh/year

assumed to be somewhat automated. The adults do not feed and thus does not require feeding, nor transportation, as they are kept in set cages. The climate system ensures appropriate ventilation of the facilities, which is very important due to the high relative humidity. The same assumption for heating as described above for the nursery is applied to heating of the rearing and breeding step of the production. Cleaning and utilities are also included for this step.

Processing The sequence used for processing of larvae and frass into end products can be discerned from figure 3.1. When the larvae is harvest-ready it is separated from the frass and ground up. From the grinding process, the puree is obtained. The ground up larvae are further processed into meal and oil by extraction and drying. The frass is dried and pelletized into a fertilizer product. Cleaning and utilities are also included for this step.

Product management The finished end products, i.e. fertilizer, puree, oil and meal, are then stored in a heated area. As with the feeding substrate, this can amount to relatively large amounts, depending on outgoing deliveries, and can thus require some internal transport within the storage facilities. Degree days were used to estimate heating demand for the factory in Norway relative to the heating demand for production in the Netherlands in this step as well. However, as this concerns finished end-products, an indoor temperature of 30°is not necessary, and the required indoor temperature is assumed to be 18°instead. Using the same database as earlier, but changing the base temperature to 18°gives a total number of 2686 degree days for Dongen and 3599 degree days for Bergen (BizEE Software, n.d.). It was therefore assumed that the heat demand is 34 % more in Bergen than in Dongen. Cleaning and utilities are also included for this step. The resource use is given per kg of product in the inventory for this step, meaning that each resource is multiplied with the total amount of products, i.e. the sum of meal, oil, puree and fertilizer.

Administrative areas support Administration is also included in this inventory, including use of electricity, heat and water. The necessary inputs to this step is given per kg fresh larvae, which supports the main functionality of the system as a whole, i.e. the production of larvae. The same assumptions regarding heating demand as used for product management is also used for administrative areas support, i.e. the heating demand is assumed to be 34 % more in Bergen than in Dongen.

Yellow mealworm production

No detailed life cycle inventory for the production of yellow mealworm has been published to this date, as the LCA studies preformed by both Thévenot et al. (2018) and Oonincx and De Boer (2012) only reports on some of the most important parameters, with no process- or technology-specific inventories. As the goal of this study is to gain insight into the contribution of the different processing steps to the environmental performance of the system as a whole, a more detailed inventory was developed in this study.

This inventory is based on careful review of the production technologies currently in use in Europe as well as correspondence with research institutions such as Inagro and the Danish Technical Institute (DTI). A processing sequence as shown in figure 3.2 was chosen as a model for yellow mealworm production. As for the BSF, the system boundaries comprise the whole production cycle of the yellow mealworm from feedstock reception and preparation through all life stages and final processing and preparation of end products. Upstream and downstream transport to and from the facility is not within the system boundary.

For the yellow mealworm inventory, a combination of data sources were used. Primary data was obtained from a research facility in Belgium, from a project called Entomatization. This project involved three partners, namely Vives, Inagro and Sirris. Primary data from their automated feeding system was used to model the feeding of the larvae, as well as the transportation of crates containing larvae back and forth between other activities, such as screening and harvesting. First-hand data was also obtained from RFA Rijlaarsdam Factory Automation B.V., which have also developed a robot for handling crates and feeding yellow mealworm. These two robots are quite different, and are therefore assigned different roles in this model.

The remaining data used to model yellow mealworm production is collected from literature. The study by Smetana et al. (2019) was used as reference for processes such as climate system, heating, product management and administration activities as this study represents best available data at this time. With regards to post-processing of the yellow mealworm larvae into end products, data from the study by Maillard et al. (2018) was used to model both the processing of larvae into whole, dried larvae as well as meal and oil. The production of yellow mealworm follows the same general outline as the BSF, i.e. feed handling, insect production, encompassing reproduction activities and bioconversion by larvae, processing into products, product management and administrative areas support.

From figure 3.2 it can be seen that this system has four outputs, namely fertilizer, made from insect excreta, whole dried larvae, larvae meal and larvae oil. Data from Maillard et al. (2018) was used to find the total amount of whole, dried larvae, meal and oil produced, while the amount of fertilizer produced was calculated based on a ratio provided by Invertapro. The calculations performed to obtain the total production amounts can be found in appendix A.2.7. In total 199 975 kg whole, dried larvae, 177 510 kg meal, 22 625 kg oil and 3 315 789 kg frass fertilizer is produced per year from 1000 tons fresh, live yellow mealworms. The final inventory for the production of yellow mealworm can be found in table 3.3.

Feed handling Different approaches can be used with respect to the handling of feed for the mealworms. Depending on the quality and quantity of the material used as feeding substrate, different procedures might be required by the competent authorities to ensure safe production of insects as food and feed. For mealworms there is also a differentiation between wet and dry substrates.

For the general inventory, as presented in this section, it is assumed that both the wet and dry feeding material is of appropriate consistency and moisture content when it arrives at the factory, and that it must only be mixed into a homogeneous mixture and stored prior to feeding. Mealworms prefer dry feeding materials, and the addition of water is therefore not included in this inventory. However, mixing of the feeding substrate into a homogeneous consistency is needed. This mixing step also allows for feeding substrate to be blended so that it has the approximately same content for each batch, which ensure nutritional consistency of the end product. Handling of feed for the yellow mealworms is modelled using data from Smetana et al. (2019), including mixing of feeding substrate, storage and cleaning. The amount of feed needed for the production of 1000 tons of fresh mealworms is 5312.5 tons per year.

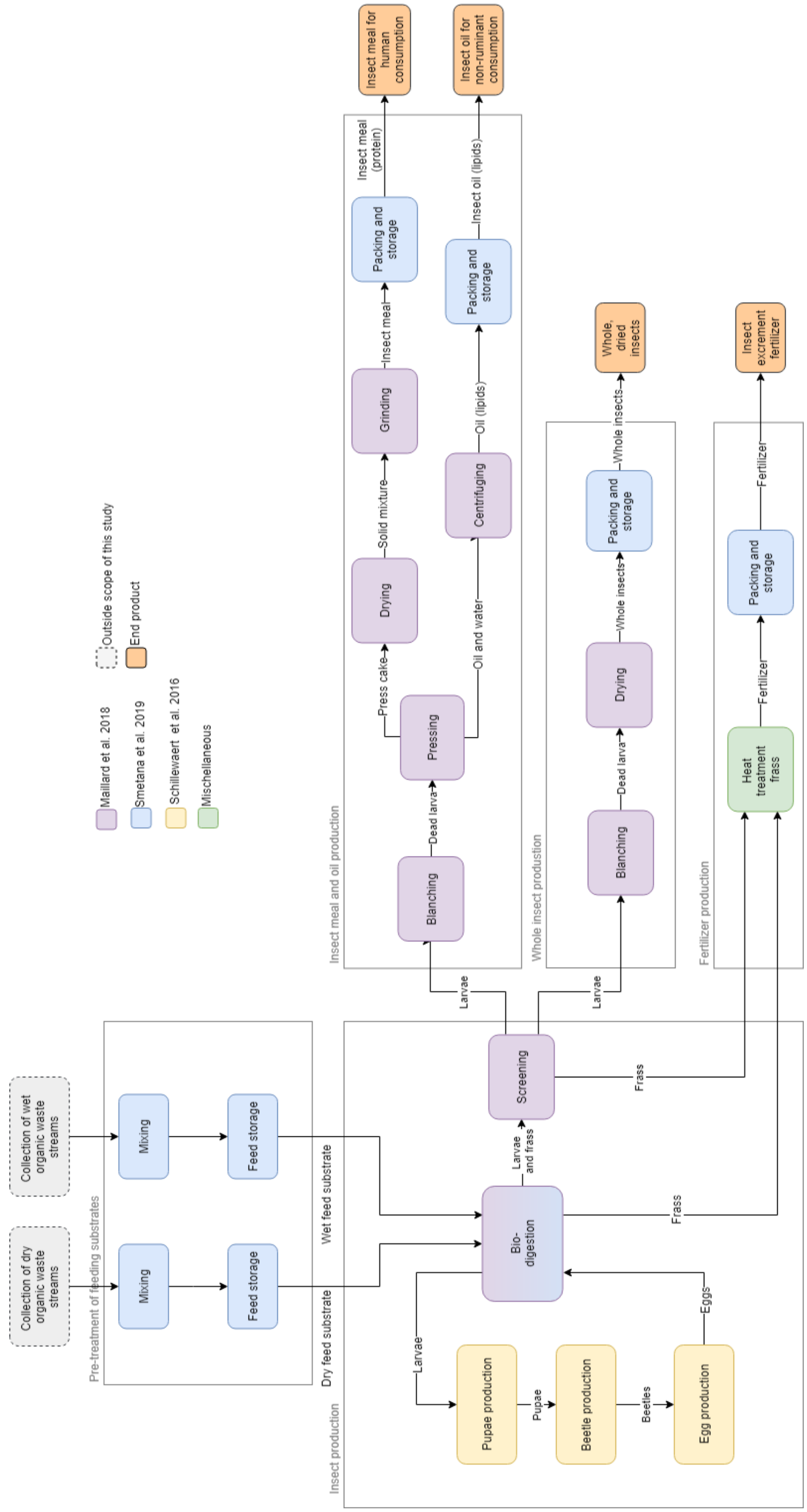


Figure 3.2: The model used for the production of mealworm production in this study, with reference sources for the different processes given in the legend.

Table 3.3: Inventory for yellow mealworm production facility

Production stage		Process	Resource	Amount	Unit	Amout for total production	Unit	Source
Feed handling		Mixing	Electricity	0.0175	kwh/kg feed	92,969	kWh/year	Smetana et al. (2019)
		Storing	Electricity	0.0025	kwh/kg feed	13,281	kWh/year	Smetana et al. (2019)
		Cleaning	Drinking water	0.6700	L/kg feed	3,559,375	L/year	Smetana et al. (2019)
Insect production	Reproduction	Screening	Electricity	0.0036	kwh/kg fresh larvae	3,602	kWh/year	Maillard et al. (2018)
		Handling	Electricity	0.5606	kwh/kg fresh larvae	560,640	kWh/year	Data from RFA Rijlaarsdam
	Bioconversion	Feeding	Electricity	0.1051	kwh/kg fresh larvae	105,120	kWh/year	Data from Inagro, Sirris and Vives
		Handling crates	Electricity	0.0263	kwh/kg fresh larvae	26,280	kWh/year	Data from Inagro, Sirris and Vives
		Screening	Electricity	0.0072	kwh/kg fresh larvae	7,204	kWh/year	Maillard et al. (2018)
		Climate system	Electricity	0.4300	kwh/kg fresh larvae	430,000	kWh/year	Smetana et al. (2019)
		Utilities	Electricity	0.1000	kwh/kg fresh larvae	100,000	kWh/year	Smetana et al. (2019)
		Heating	Heating	0.7422	kwh/kg fresh larvae	742,203	kWh/year	Smetana et al. (2019)
		Cleaning	Drinking water	16.141	L/kg fresh larvae	16,141,000	L/year	Smetana et al. (2019)
Processing	All larvae	Handling crates	Electricity	0.0160	kwh/kg fresh larvae	16,000	kWh/year	Data from RFA Rijlaarsdam
	Meal and oil	Screening	Electricity	0.0036	kwh/kg fresh larvae	1,801	kWh/year	Maillard et al. (2018)
		Heat treatment	Heating	0.0630	kwh/kg fresh larvae	31,517	kWh/year	Maillard et al. (2018)
		Pressing	Electricity	0.0625	kwh/kg fresh larvae	31,250	kWh/year	Maillard et al. (2018)
		Centrifugation	Electricity	0.0006	kwh/kg fresh larvae	298	kWh/year	Maillard et al. (2018)
		Grinding	Electricity	0.0090	kwh/kg fresh larvae	4,500	kWh/year	Smetana et al. (2019)
		Drying	Heating	0.5633	kwh/kg fresh larvae	281,655	kWh/year	Maillard et al. (2018)
		Evaporation	Heating	0.4295	kwh/kg fresh larvae	214,763	kWh/year	Maillard et al. (2018)
	Whole dried	Screening	Electricity	0.0036	kwh/kg fresh larvae	1,775	kWh/year	Maillard et al. (2018)
		Heat treatment	Heating	0.0629	kwh/kg fresh larvae	31,448	kWh/year	Maillard et al. (2018)
		Drying	Heating	0.6749	kwh/kg fresh larvae	337,469	kWh/year	Maillard et al. (2018)
	Frass	Heat treatment	Electricity	0.0038	kWh/kg frass	12,435	kWh/year	Miscellaneous
Product management		Storage	Electricity	0.0760	kwh/kg of product	282,424	kWh/year	Smetana et al. (2019)
		Utilities	Electricity	0.0340	kwh/kg of product	126,348	kWh/year	Smetana et al. (2019)
		Cleaning	Drinking water	2.6100	L/kg of product	9,699,046	L/year	Smetana et al. (2019)
		Heating	Heating	0.2786	kwh/kg product	1,035,256	kWh/year	Smetana et al. (2019)
Administrative areas support		Administration	Electricity	0.1300	kwh/kg fresh larvae	130,000	kWh/year	Smetana et al. (2019)
		Administration	Drinking water	1.8200	L/kg fresh larvae	1,820,000	L/year	Smetana et al. (2019)
		Administration	Heating	0.0588	kWh/kg fresh larvae	58,782	kWh/year	Smetana et al. (2019)
				Totals	Electricity	1,937,927	kWh/year	
					Drinking water	33,640,571	L/year	
					Heating	2,753,079	kWh/year	

On one hand, using the data from Smetana et al. (2019) simplifies a part of the production which could potentially require resource intensive processes like freezing or drying. On the other hand, simplifying it to processes which have been reported from real-life production of this particular type of system (i.e. insect production) could potentially increase the credibility of the study as a whole. Using existing, representative data rather than making more assumptions to facilitate the modeling of other possible processing sequences is thus recognized as reasonable within the scope of this study.

Insect production In all stages of the life cycle, the mealworms live in plastic crates where they must be provided with both dry and wet feeding substrate. Several options for how these facilities can be operated was described in section 2.5.5, but for this study the system developed by Inagro, Vives and Sirris in Belgium was chosen for use in the bioconversion step of the model, as primary data for the operation of this system could be obtained directly from the designers of the system. This modular cell-based system only performs automated feeding of wet feeding substrate, but for the purposes of this study is was assumed that the technology could be modified to provide dry feeding substrate as well. For this technology it is assumed that this extended functionality can be implemented with no cost in terms of increased electricity consumption or service time for each crate.

It is also assumed that the feeding robot, which moves back and forth on the outside of the cells, can be modified to perform the operation of transporting crates for further processing in addition to the task of feeding. This operation is assumed to be performed by a different robot than the one providing feed, meaning a system where the cells are handled from two sides, i.e. the back-side and the front end, as shown in figure 3.3. This functionality is assumed to be a simple modification of the existing technology, where the robot pulls one stack of crates at a time onto itself, and transports the stack along the rail on which it moves to a pre-defined point, where the stack is transferred to another part of the facility for further processing.

Figure 3.3: Schematic of a cell-based insect production facility where the cells are handled by robots (shown in green) from both the back and the front. Courtesy of Inagro, Sirris and Vives (Schillewaert et al., 2016).

This cell-based system is currently operating at pilot scale at Inagro's facilities in Belgium, from which primary data for operation was obtained. The system uses 1.5 kW of electricity and it operates for 8 hours per day, servicing 4000 crates in this time (Coudron, 2019). These operational conditions were extrapolated to service an entire yellow mealworm production facility. The calculations performed to find the number of robots necessary to facilitate large-scale production and the total electricity consumption of these robots can be found in appendix A.2.1.

It should be noted that the number of robots needed to service the desired production depends on to which extent the vertical farming concept is utilized. All production cells could be built at ground level, resulting in the need for a relative large production area. However, if cells are stacked on top of each other, this would enable more efficient use of the floor space. On the other hand, this would require more robots, as the robots are only designed to move in one dimension. For the purposes of this study, it is assumed that two cells are stacked on top of each other.

Keeping the mealworms in small, separate cells provides the opportunity for regulating environmental conditions such at temperature, lighting and humidity in each cell individually. However, as the pilot installation in Belgium has not developed into this stage yet, such primary data was not available. The data provided for the climate system, heating, cleaning and utilities for the insect rearing and breeding stage in the previously discussed study by Smetana et al. was therefore used to represent the same activities in the mealworm system.

Attention should be paid to the large uncertainty this assumption introduces in this study. As described in section 2.4, the yellow mealworm and the BSF do not thrive in the exact same environmental conditions. The two species differ particularly with respect to optimal temperatures and relative humidity, as the optimum temperature for BSF is around 30 °C at 50 - 70 % relative humidity, and the optimal temperature for the yellow mealworm is around 27 °C at 60 - 70 % relative humidity. The maintenance of these conditions is linked to high energy consumption, and have been documented to have large impacts of the total environmental performance of insect production systems, as discussed in section 2.3. Smetana et al. (2019) found that 33 % of the total electricity use and 32.5 % of total natural gas used for heat was used by the climate system in the facility in their model, and energy use is thus an important impact pathway in the system as a whole. This assumption is therefore a significant source of uncertainty in this study.

To lower this uncertainty, adjusting the heating demand according to degree days was also implemented here, similar to what was done in the inventory for the BSF. A total number 5770 degree days was obtained for Dongen, and 6844 degree days was obtained for Bergen, using the same database as for the BSF, but adjusting the base temperature to 27 °C (BizEE Software, n.d.). The heating demand for the insect production step was therefore increased by 19 % relative to the heating demand reported by Smetana et al. (2019) based on the percentage difference in degree days, i.e. from 0.600 m^3 natural gas to 0.714 m^3 natural gas, which was converted to kWh by multiplication with a factor of 10.395 kWh per m^3 natural gas, resulting in a total of 0.7422 kWh thermal energy per kg fresh mealworms.

For climate system operation, cleaning and utilities for the insect production stage, the exact data as reported by Smetana et al. (2019) was used. In addition, the yellow mealworm must be screened at intervals, as discussed in section 2.5.5. Data for this processing step was obtained from Maillard et al. (2018), as the processing technology investigated in this study includes a screening process of the yellow mealworm specifically. The calculations made to obtain the electricity consumption per kg mealworms screened can be found in appendix A.2.2.

The insect production step also includes a reproduction stage. Technically, the reproduction stages of the yellow mealworm life cycle could also take place in the same types of cells as the bioconversion process. However, as reproduction activities require more frequent handling, as eggs have to be sorted from the crates of the adults to prevent cannibalism, this stage was assumed to make use of another technology. The robot developed by RFA Rijlaarsdam Factory Automation B.V., as described in section 2.5.5, was chosen for this purpose. The reproduction facilities are therefore not cell-based, but consists of an open space serviced by robots at a set interval.

The robot is rated at a maximum power consumption of 10 kVA, which corresponds to 8 kW, and is reported to de-palletise and palletise 2000 crates in 8 hours (Rijlaarsdam, 2019). To enable calculations of the reproduction step, a ratio of 1 crate for reproduction for every 2 crates of mealworm larvae at the bioconversion step was used, based on estimations from Invertapro. The full calculation of the number of robots needed to serve the whole reproduction facility and the total energy consumption associated with this operation can be found in appendix A.2.2.

Processing After the mealworm larva have completed the bioconversion process, they are screened and then further processed into products. After example by Invertapro, who is producing whole, dried mealworm larvae, and has also started producing ground larvae for inclusion in other products such as bread, both end products was modelled in this study. The total production of 1000 tons of fresh larvae is therefor separated into two different processing pathways after harvest, where 500 tons goes to the production of whole, dried larvae, and 500 tons for production of insect meal.

One important modelling choice was which slaughtering method to use. Freezing is common today, but researchers at both Inagro and DTI specified that killing using hot water is more likely to dominate in the future, to ensure proper decontamination of the insects, and blanching was therefore chosen in this study (Andersen, 2019; Coudron, 2019). A recent study by Maillard et al. (2018) describes three different scenarios for processing the larvae of the yellow mealworm into insect meal, using blanching as slaughtering method. In this recent study, the processing steps are described in detail, and mass and energy flows are provided based on pilot scale trials. Two of the scenarios from the study by Maillard et al. were therefore chosen as representative for the desired production processes modelled in this study.

The processing procedure for the whole, dried larvae is shown in figure 3.4. These processes were originally designed to produce meal, but by removing the grinding step the resulting product is whole, dried larvae in place of meal. The three processing steps is thus screening, heat treatment and drying. The screening is preformed by a vibrating conveyor, which removes the frass. Thereafter the larvae are blanched in hot water keeping a temperature of 90 - 95°C before it is dried to reduce the moisture content down to 5 - 10 %. The calculation of energy use in the different processing steps, based on the information provided in Maillard et al. (2018), can be found in appendix A.2.4.

The processing procedure for the insect meal is shown in figure 3.5. This is a more complex process involving more processing steps. After screening and blanching, which is similar to the processes for production of whole, dried larvae, the larvae are pressed, resulting in a press cake and a press liquor. The press liquor is centrifuged, after which the lipids are separated out as oil. The proteins remaining in the press liquor is decanted and processed through an evaporator before it is combined with the press cake for drying and grinding into meal. This ensures a high protein content in the meal. The calculation of energy use in these processing steps can be found in appendix A.2.5. No data was provided for the grinding step in Maillard et al. (2018), so the data for the grinding process as reported by Smetana et al. (2019) was used.

As can be seen in figure 3.5, the processing of yellow mealworm into larvae produces wastewater. However, the amounts and quality of this wastewater was not reported in the study by Maillard et al., and specific data for this output from the system could therefore not be obtained. In stead of process specific data, a general value for wastewater from the whole production process was used based on the LCA performed by Thévenot et al. (2018). Here it is given that 2.538 kg of raw sewage sludge is produced per 1 kg of insect meal from the yellow mealworm larvae, which

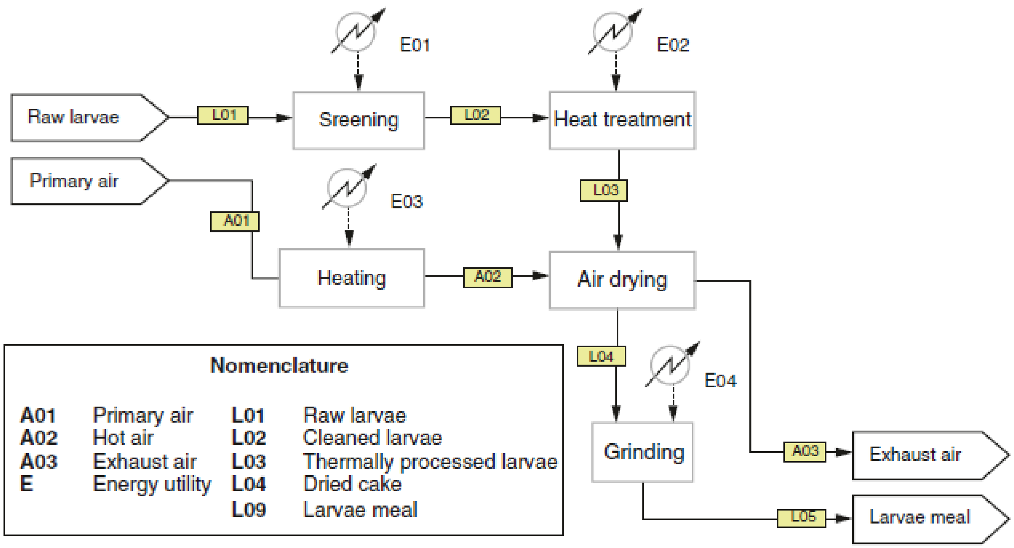


Figure 3.4: Sequence for processing yellow mealworm larvae into whole, dried larvae. The grinding step is omitted from this study. From Maillard et al. (2018).

means that from the production of yellow mealworms, a total of 450 521 kg raw sewage sludge is produced per year. The calculation for this amount can be found in appendix A.3.2.

Before the harvest-ready larvae are processed, either into whole, dried larvae or meal and oil, the crates containing the larvae must be received from the production cells. This crate-handling is assumed to be performed by a robot of the type developed by RFA Rijlaarsdam Factory Automation B.V., similar to the robots used for the reproduction stage. This robot is specialized to efficiently stack and de-stack crates, and is thus assumed to be able to carry out the task of taking each crate from the transportation robot, and sending it for further processing. The calculations related to this handling of crates can be found in appendix A.2.3.

From the screening activities, both during bioconversion, reproduction and after harvest, the insect excreta is screened from the larvae and collected. This material is dry and odourless, and can be used as fertilizer. However, it has to be thermally treated before it is used, to ensure that it is hygienic. Invertapro reports that their frass is heated to 70 °C for 1 hour, which satisfies the requirements by the Norwegian Food Safety Authority. This procedure is therefore also adopted for the post-processing of frass in this study.

However, data availability on such operations are not readily available. The inventory reported by Smetana et al. (2019) does not segregate between drying of the insect excreta and drying of larvae, and can therefore not be used as a proxy for heat treatment of frass as this would most likely largely overestimate the resource consumption for this activity. The drying processes described by Maillard et al. (2018) are dimensioned for use on larvae, which have a much higher moisture content than the frass, and these processes are therefore not suited for modelling the drying of frass either. Lacking specific data, and online search was preformed, resulting in the use of an industrial oven with a reported power rating of 1.5 kW and a capacity of 480 kg per batch as a model for the post-processing of frass. The calculation performed to obtain the final resource demand of this processing step can be found in appendix A.2.6.

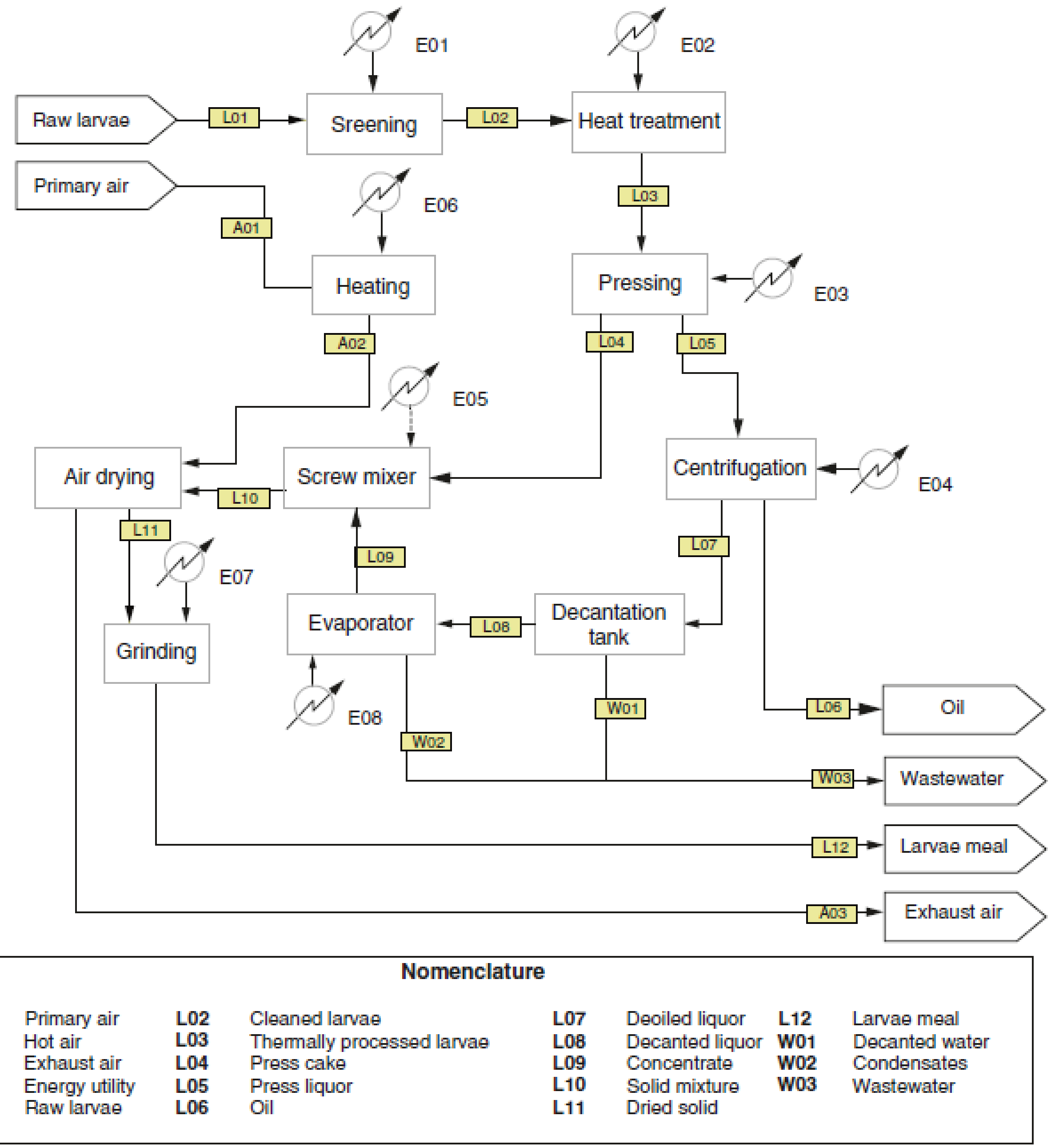


Figure 3.5: Sequence for processing yellow mealworm larvae into insect meal. From Maillard et al. (2018).

Product management The inventory for product management is taken directly from Smetana et al. (2019), and includes the same activities as for the BSF. As for BSF production, the heating demand was adjusted by the relative difference in degree days, resulting in 34 % larger heating demand in Bergen than in Dongen based on an indoor temperature of 18 °C. The resource use is given per kg of product in the inventory for this step, meaning that each resource is multiplied with the total amount of products, i.e. the sum of whole, dried larvae, meal, oil and fertilizer.

Administrative areas support Similar to product management, the administrative area support is modelled using the exact inventory from Smetana et al. (2019), only adjusted for degreee days for heat demand at the same percentage as the product management heating demand (as these areas are assumed to require the same indoor temperature of 18 °C).

3.2.2 Capital goods

Only two of the existing LCAs on insect production systems have included capital goods in the inventories for their models (Thévenot et al., 2018; Roffeis et al., 2015). Though Thévenot et al. (2018) included construction of facilities and the use of machinery in their study, the contribution from this was not mentioned in the results nor in the discussion, and can thus be assumed to have had little impact. Roffeis et al. (2015) also included the construction of facilities, but found it to contribute little to the total environmental impact in a sensitivity analysis. Salomone et al. (2016) did not originally include capital goods in their study, but included it in a sensitivity analysis. In contrast to Roffeis et al., Salomone et al. found that the total environmental impacts were notably influenced by the inclusion of infrastructure, machinery and equipment, particularly from the use of reinforced concrete.

Though there seems to be no consensus on the inclusion of capital goods among existing LCAs of insect production systems, a more holistic system approach can be used to determine how best to approach this subject. Insect production, as it is described in this study, fulfills three functions:(1) waste management of organic by-products, side streams and non-utilized materials, (2) protein production for use in animal feed and (3) protein production for use as human food as an alternative to other animal protein sources. With this in mind, it is relevant to survey what approach is common with regards to capital goods in environmental impact analysis of these kinds of systems.

Laurent et al. (2014) reported that only 12 % of a total of 222 LCA studies of waste management systems included capital goods. Similarly, Vellinga et al. (2013) stated that capital goods are excluded from the industrial processing of feed ingredients in the assessment of GHG emissions from feed production and utilization. Agri-Footprint, a comprehensive life cycle inventory database for agriculture products, does not include capital goods (BV, 2015). A guidelines on the environmental performance assessment of animal feed supply chains presented by the Food and Agriculture Organization (FAO) also excludes capital goods (FAO, 2014a). Based on the fact that few of the existing LCAs on insect production systems include capital goods, and the seemingly systemic choice of not including capital goods in comparable systems, it was chosen to not include capital goods in this study. This decision was also based on there not existing an industrial facility in Norway from which such an inventory could be obtained, and also a lack of these specific data in the literature. Including capital goods in this study would thus introduce significant uncertainty.

3.2.3 Transport

As the focus of this study is to investigate how the different processing steps in insect production affect the environmental performance of the system as a whole, a gate-to-gate approach was chosen for this study. Transport of feed material to the factory, and similar transport of the finished products to the market it therefor excluded from this study. This choice represents a methodical difference from most other studies on insect production systems. However, with the goal of providing a foundation for comparison with different comparable products in mind, making the results dependant on a specific transportation mode or distance creates an undesired lock-in.

It can also be argued that the exclusion of transport will not significantly affect the results as the main goal of establishing insect production, at least as defined by Invertapro, is to create a *local* solution for organic by-products, side-streams and waste streams. The utilization of local resources is emphasised, and long transportation distances should thus be avoided. Compared to the production of other feed resources, such as soy meal or fish meal, the transportation distances from primary production to both processing plants and end users are significantly lower for insect production. A similar argument was made by Halloran et al. (2016), where it was pointed out that insect production is currently a local industry relying on local resources, in comparison to the livestock industry which is a global industry generally associated with long transport distances.

This could also be discussed from a Norwegian point of view. Approximately 90 % of the cultivated land area in Norway is used for feed production, which alludes to a high level of self sufficiency and independency from global markets for Norwegian farmers. However, there is still a noticeable limit on the availability of local feed resources, because the total cultivated area in Norway only constitute about 3 % of the land area, due to climatic conditions (Norwegian Ministry of Agriculture and Food, n.d.). As a result, Norway is dependent on feed imports, as can be seen from the annual report of ingredients used in Norwegian production of feed. 43 % of all feed ingredients used in Norwegian feed production in 2018 was imported. For protein-rich ingredients, the imported ingredients made up 96 % of the total protein-rich ingredients used in Norwegian feed in 2018 (Norwegian Agriculture Agency, n.d.[a]). The exclusion of transport for this insect production system can thus be assumed to be representative, as this is arguably a more locally founded system than other agricultural systems.

3.2.4 Direct GHG emissions

Insects produce greenhouse gases (GHGs) through respiration and data on GHG production from Oonincx et al. (2010) is used to model the direct emission of GHGs from insects in this study. However, no data exists on the emission of GHGs from the BSF, and only GHG production by the yellow mealworm is therefore included in this study. The GHGs considered by Oonincx et al. comprises CO_2, CH_4 and N_2O. However, CO_2 produced by respiration from livestock is not included as a source of direct GHG emissions, as the carbon respired by the insect originates from the feeding material, which again originates from the air, and is thus a part of the natural carbon cycle. Only CH_4 and N_2O emissions are thus considered in this study.

For the yellow mealworm (*Tenebrio miolitor*), N_2O production of 1.5 mg per kg of bodymass per day was registered, while no CH_4 were reported (Oonincx et al., 2010). The total bodymass of insects in the production facility at any given day cannot be determined without introducing large uncertainty to the study. The total GHG emissions are therefore estimated based on the total production amount of larvae, i.e. bodymass of live fresh insects, per year. The calculations performed to estimate the total direct GHG emissions from the yellow mealworm can be found in appendix A.3.1, resulting in a total N_2O-emission of 548 kg per year for the yellow mealworm.

3.3 Case study description

The model description of an insect production system as presented in the previous section represents only the technological installations and their quantitative inputs from the technosphere, namely electricity, heat, water and feed material. This production facility could essentially be built anywhere in the world with access to these resources. However, the goal in this study is to investigate the potential environmental impacts from such a system established in Norway specifically, and emphasis was therefore put on the input of available Norwegian resources.

More specifically, the insect production system described in this study is assumed to be established in Bergen, in the Western region of Norway. This is the centre of the operative area for BIR, and is thus a natural choice for a facility operated by Invertapro for handling organic material collected by BIR and their partners. BIR collects municipal waste from the inhabitants of Bergen and the surrounding area, in addition to collecting and treating waste streams from businesses through another branch of their company, BIR Bedrift. BIR is as such able to cover a large variety of different organic resources which can potentially become feed for insects.

Assuming the location of this insect production system to be Bergen also allows for the specific modelling of energy sources which are available in this area. Invertapro and BIR are collaborating on the up-scaling of insect production technology, but exactly where a large-scale facility will be built has not been decided yet. For the purposes of this study, the exact location of the modelled system is assumed to be Rådalen, on the industrial area on which the municipal waste incineration facility operated by BIR is located. This allows for use of district heat from the incinerator in the insect production system.

3.3.1 Feed material

As previously mentioned in section 2.6, regulatory restrictions prevent the use of the largest available organic waste stream , i.e. food wastes from households, restaurants and catering. As of today, only vegetal resources are allowed as feed for insects. To represent this situation, locally available side-streams and by-products from the agricultural sector and food industry on the West coast of Norway were modelled as feeding substrate for insects in this study.

By-products from agriculture

According to Lindberg et al. (2016), the largest residual raw materials in Norway of vegetal origin come from the production and processing of cereals and vegetables. This residual raw material consist primarily of wheat bran, oat hulls, barley hulls and spelt hulls from cereal production, in addition to residual raw materials from industrial processing of vegetables and potatoes. The availability of residual raw materials on the West coast of Norway was investigated by Western Norway Research Institute in 2017 (Andersen et al., 2017). The conclusion was that there is limited availability of residual raw material of vegetal origin in this region, primarily caused by limited agricultural production of cereals and vegetables in this region. However, there is a notable quantity of spent grains from breweries, amounting to a total of 3174 tons per year.

Side-streams from the food industry

Additionally, there exists vegetal material in the form of food loss from the food value chain. On the West coast of Norway, food loss from bakery and dairy production represents the largest source of vegetal residual raw material. In a report prepared by the author of this study for Invertapro in 2018, it was calculated that a total of 1432 tons of food loss from the bakery industry and 7136 tons of food loss from the dairy industry is produced on the West coast of Norway each year (Liverød, 2018).

Additional feed resources

Brewer's spent grains and food loss from the bakery and dairy industries are assumed to form the base of the vegetal feed scenario. However, these resources, i.e. spent brewer's grains, dairy and bakery food loss, only represent 11 742 tons of feeding substrate in total. The remaining 18 258 tons needed to reach full capacity of 30 000 tons per year are therefor assumed to be supplied by wheat bran. This is a by-product from processing of wheat cereal into meal which is commonly used as feeding substrate for insects (Thévenot et al., 2018). However, in contrast to the other residual raw materials described here, wheat bran is already utilized as a feed ingredient in Norway and therefor has an economic value.

Allocation of feeding materials

With reference to the allocation method chosen for this study, as described in section 3.1.2, the cut-off principle is used with respect to environmental impacts for the feed substrate. This means that no burden is allocated to food loss i.e. brewer's spent grains and food loss from bakery and dairy production, which are in terms of this model regarded as waste products from their respective production processes. Essentially, these residual raw materials have no economic value, and can thus be considered to be waste products from their respective processes of origin. However, this does not apply to wheat bran, which is a commercial feed commodity, and is accordingly allocated some of the environmental impacts from the production and processing of wheat cereal (BV, 2015).

The Agri-footprint database with economic allocation was used for the inventory of the wheat bran. The primary data used as a foundation for this database mainly originates from Belgium, Germany and the Netherlands. For wheat bran specifically, all these countries rely on import of wheat from other countries for the milling of wheat grains into end products (flour, bran, etc.), which entails relatively long transport distances by various means of transport. Using such processes is thus not a particularly good proxy for Norwegian wheat bran produced from Norwegian wheat as intended in this study.

Therefore, a new background process for Norwegian wheat bran was made in Simapro, assuming the same technical aspects as the milling process given for wheat milling in Belgium, but with Norwegian wheat grain as input. The quality of the data for the Norwegian wheat grain is equally good as the data for the other countries given in the Agri-footprint database, as this process is adapted by use of the same background data sources for all countries. For example, FAO statistics are used for crop yield for each specific grain type for each specific country, and the quality of these data can thus be assumed to be equally representative (BV, 2015). The new process for wheat bran is also adjusted so that the input of heat and electricity for wheat production and all subsequent processing before the wheat becomes bran is based on Norwegian energy resources. All transport elements are also removed, as this is excluded from this study as defined in section 3.2.3.

As the yellow mealworm is most particular with respect to its feeding substrate, needing both dry and wet feeding substrate, the side-streams which are most suited for this production are allocated to the mealworms. This means that the the whole amount of brewer's spent grain and food loss from bakery production is allocated to the yellow mealworms. The food loss from dairy production is assumed to have a higher moisture content, and is thus assumed to be suitable for BSF. Wheat bran is provided for both the yellow mealworm and the BSF, making up the difference between the food loss and full capacity.

Based on the necessary feeding substrate input as described in section 3.2.1, i.e. 2187.5 kg dry feed substrate and 3125 kg wet feed substrate for the yellow mealworms and 24687.5 kg feeding substrate for BSF per year, the distribution of the amounts of vegetal side-streams and by-products as described in this section is shown in table 3.4. There is 49 tons more available spent brewer's grains than what is needed for the mealworms, which is is provided for the BSF.

Table 3.4: Scenario 1: Vegetal side-streams and by-products

Feeding substrate	Amount	Unit	Comment
Brewer's spent grains	3125	tons/year	For mealworm
Food loss from bakery industry	1432	tons/year	For mealworm
Food loss from dairy industry	7136	tons/year	For BSF
Wheat bran to mealworm	756	tons/year	For mealworm
Wheat bran to BSF	17503	tons/year	For BSF
Total	30000	tons/year	

3.3.2 Electricity input

Electricity from the Norwegian power grid was assumed as input for all processes requiring electricity in this model. However, when modeling electricity consumption, a conscious choice of which power market is assumed as a system boundary for the electricity must be made. Electricity is difficult to store in large quantities and consumption and production must therefor match at all times. Norway is therefore tightly connected to its neighbouring countries through both physical and financial energy trade, and is part of the Nordic power market, NordPool. The Nordic power market is further interconnected with the European power market. According to the 2017 declaration for the Norwegian energy sector, only 46 % of the energy which was *consumed* in Norway in 2017 was from renewable sources, even though 98 % of all electricity *produced* in Norway in 2017 was from renewable sources (Norwegian Water Resources and Energy Directorate, 2018). This is primarily caused by the sale of Guarantees of Origin (GOs), essentially "selling" the renewable quality of Norwegian hydro power to consumers in other countries which are willing to pay a premium for renewable energy.

There are thus three different options for modelling Norwegian grid power: 1) Norwegian electricity mix based on Norwegian power production, 2) Nordic electricity mix or 3) European electricity mix, of which all can be considered to be reasonably representative for the electricity consumed in Norway, depending on which perspective one adopts. Which electricity mix is used in the modelling will most likely have a relatively large impact on the total environmental impacts from the insect production system as the CO_2 emission factor for these electricity mixes are very different. Norwegian Water Resources and Energy Directorate (2018) calculated a CO_2 emission factor of 16.4 g per kWh of Norwegian production mix in 2017, and also cited the European electricity mix factor to be 345 g/kWh in 2011 according to the World Energy Outlook 2013 published by IEA. The Nordic electricity mix was reported to have a CO_2 emission factor of 59 g/kWh in 2013, according to IEA (2016).

Using Norwegian production mix as electricity source in this study, thereby assuming the Norwegian power system to be completely isolated, would most likely significantly underestimate the environmental impacts from this resource for the reasons explained above. It was therefore decided to use Nordic electricity mix for the primary modelling of all use of electricity in this study, as this represents the physical power interactions more accurately, without introducing the uncertainty of using European electricity mix as an average. It can also be assumed to be a form of middle ground between the two extremes, i.e. Norwegian production electricity mix and European electricity mix.

3.3.3 Heat input

The factory for production of BSF and yellow mealworm is in this study assumed to be situated on the industrial area in Rådalen outside Bergen in Norway. In Rådalen, BIR operates an incineration facility for municipal waste from the area, which generates heat that is distributed in a district heating network by the local energy company BKK Varme. District heating originating from this incineration facility is assumed as input for all heating processes in this study. However, the Ecoinvent database does not contain such a process, and a proxy must therefore be used. In the product declaration of CO_2 and NO_X emissions associated with the district heating provided from the incineration facility in Rådalen, reference is made to the ZEB (Zero Emission Building) guidelines for handling district heating from waste incineration. ZEB argues that greenhouse gas emissions from district heating is comparable to the emissions from incineration of natural gas (Horne, 2019). This definition is used in the product declaration for the heat produced from the waste incinerator in Rådalen, and natural gas is therefore used as a proxy for district heating from municipal waste in this study.

3.3.4 Land use

Some of the inputs used in this system requires indirect use of land area, for example for cultivation of wheat for production of wheat bran for use as feeding material. In addition to indirect land use, direct land use is also associated with the production in terms of the land occupied by the production facilities. As discussed in section 3.1.2, in this study only environmental impacts resulting in land use of arable land, i.e. agricultural land occupation is considered. The impact categories urban land occupation and natural land transformation which are characterized as a part of the ReCiPe method were excluded from this study, as this category is seldom included in impact assessments of insect production systems. The production facilities modelled in this study are assumed to be established on an industrial site, which means that no additional agricultural land is used. Combined with the limited data available on the physical dimensions of this type of insect production facility, direct land use is therefore not included in this study, as this would not add any more precision to the results.

3.4 Comparisons to other production systems

One of the research questions to be explored in this study is the environmental performance of products derived from insects compared to the environmental performance of similar food and feed commodities. Complete LCAs of different food and feed commodities for different uses and from different production systems can be found in literature (eg. Boissy et al. (2011) or Silva et al. (2018) for feed ingredients used in fish feed, Schmidt (2015) for oil products and Salou et al. (2014) or de Vries and de Boer (2010) for livestock products). However, to ensure comparability of results, separate life cycle impact assessments were preformed in this study for food and feed commodities found in the generic databases in SimaPro, i.e. Ecoinvent and Agri-footprint. This limits the dependency on system specific variables for the different production systems.

For data from the Agri-footprint database, the datasets based on economic allocation for products in the Netherlands were used. All products were analysed for a functional unit of 1 kg product using the ReCiPe hierarchist midpoint characterisation method and the Cumulative Energy Demand method similar to the insect products. The same environmental impact categories were considered, i.e. climate change, terrestrial acidification, freshwater eutrophication, agricultural land occupation, water depletion and cumulative energy demand.

For the oil derived from both the BSF and the yellow mealworm, oil products commonly used in fish feed formulations were used as basis for comparison, as the intended market for this production system is the Norwegian aquaculture industry. This includes palm oil, soybean oil and fish oil, according to Sørensen et al. (2011). For the BSF meal, common aquaculture high-protein feed ingredient are used for comparison, including fish meal, soybean meal and rapeseed meal, by example of the comparisons made by Smetana et al. (2019). The benchmark LCA impacts for these products were obtained by Simapro modelling of the Ecoinvent process shown in table 3.5, except from the fish meal and fish oil, which were not available in neither of the available databases. Data from Silva et al. (2018) is therefore used, even though the impact categories considered in that study are not exactly the same as the ones investigated in this study.

Table 3.5: Processes used to find environmental impact of benchmark products

Product	**Process modelled**	**Database**
Palm oil	Palm oil, refined {GLO}, market for, Alloc Rec, U	Ecoinvent 3
Soybean oil	Soybean oil, refined {GLO}, market for, Alloc Rec, U	Ecoinvent 3
Soybean meal	Soybean meal, from crushing (solvent), at plant/NL Economic	Agri-footprint
Rapeseed meal	Rapeseed meal, from crushing (solvent), at plant/NL Economic	Agri-footprint

For comparison to the high-protein products from the yellow mealworm production system, conventional high-protein animal livestock products were assessed after example by Oonincx and De Boer (2012), including pork, chicken and beef. Due to limited availability of these products in the databases, comparable data was obtained from a review of life cycle assessments of livestock products preformed by de Vries and de Boer (2010). For the BSF puree, the only comparable product considered is assumed to be chicken meat, for which comparable data was obtained from Smetana et al. (2019).

Chapter 4

Results

The functional unit for this study is 1 kg of product, and the results are thus presented for 1 kg of each of the six main products of this insect production, namely whole, dried larvae, meal and oil from the yellow mealworm and meal, oil and puree from the BSF.

4.1 Yellow mealworm production

The total potential environmental impact for each of the six impact categories considered in this study for the production of yellow mealworm larvae products can be seen in table 4.1. The impact for yellow mealworm oil is substantially higher than the impact from meal and whole, dried larvae in all impact categories presented. This is caused by the total production amount of the oil, which is much lower than the production of meal. Even though impacts are allocated evenly between meal and oil, the impacts associated with oil is thus more, as more resources are required to produce 1 kg of oil in comparison to 1 kg of meal. However, the relative distribution of impacts between production stages and processes are identical for these two products, as these two products go through the exact same processing, and are allocated the same relative amount of the burden of these processes. The relative contribution of the different production stages and processes are thus only presented for meal in this section, as the same contribution patterns applies for the oil.

Table 4.1: Impact results for midpoint categories for products derived from yellow mealworm (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	Oil	Whole dried larvae
Climate change	kg CO_2 eq	1.667	13.081	2.733
Terrestrial acidification	kg SO_2 eq	0.011	0.088	0.019
Freshwater eutrophication	kg P eq	0.000	0.003	0.001
Agricultural land occupation	m^2a	1.281	10.051	2.262
Water depletion	m^3	0.083	0.655	0.146
Cumulative energy demand	MJ	39.121	306.930	64.744

The whole, dried larvae is allocated more of the impacts from the production than meal and oil, due to its economic value, as discussed in section 3.1.2. However, processing fresh live larvae into whole, dried larvae is less resource intensive than processing fresh live larvae into meal and oil, and the final impacts of the whole, dried larvae is thus not very much larger than the impacts of meal. The resource use in the processing stage is as such the only difference in the production setup between meal and whole, dried larvae, as both products stem from the feed handling, reproduction and bioconversion of the yellow mealworms.

From table 4.1 it can be seen that the total impact in the categories terrestrial acidification, freshwater eutrophication and water depletion are very small. However, attention must be paid to the unit used for each impact category. For terrestrial acidification potential and freshwater eutrophication potential, values are given per kilogram, even though these types of impacts are typically in the scale of grams rather than kilograms. Similarly, water depletion is given per cubic meter, which corresponds to 1000 liters, which puts these values into a more relatable context.

The cumulative energy demand is characterized by the same trends as the other impact categories in terms of the total impact for each product. The production of yellow mealworm oil clearly requires the largest energy supply, followed by the whole dried larvae and then the meal. 56 % of the cumulative energy demand for the production of 1 kg of meal (and thus also similar for oil) in this system is supplied by non-renewable, fossil energy resources, 22 % is supplied by non-renewable nuclear energy resources, 18 % is supplied by renewable water resources and 3 % is supplied by renewable biomass energy resources.

The fossil energy resources are primarily used to cover heat demand using natural gas. The nuclear resources originate from the Swedish contribution to the Nordic electricity mix, and is used for processes requiring electricity. The energy supplied by renewable water is also used for electricity, as this mainly comes from the Norwegian contribution to the Nordic electricity mix. Biomass is used in co-generation of heat and electricity in both Sweden and Finland, and electricity from this co-generation is thus also part of the Nordic electricity mix, further supplying the remaining energy demand for electricity. The share of non-renewable energy resources used for the production of meal is 78 %. The whole, dried larvae have a similar impact pattern for the contribution to the cumulative energy demand, totalling a non-renewable energy share of 77 %.

4.1.1 Relative impacts of production stages

The relative impacts of each of the production stages in addition to the feeding substrate and sewage sludge is shown in figures 4.1 and 4.2 for yellow mealworm meal and dried whole larvae respectively. From these figures it can be observed that the feeding substrate provided for the mealworms contributes greatly to most of the impact categories considered in this study. When considering these impacts it is important to keep in mind that it is only the wheat bran which contributes to these impacts, as the brewer's spent grain and the food loos from bakeries were not allocated any impacts in this study. For the meal, the feed contributes to 19 % of total climate change impact, 60 % of terrestrial acidification impact, 78 % of freshwater eutrophication and 85 % of total agricultural land occupation. Somewhat surprisingly, the mealworm feed does not significantly contribute to water depletion. This is caused by the use of generic Ecoinvent processes for the production of wheat bran from Norwegian wheat. The process of producing Norwegian wheat in Ecoinvent does not require any water, based on a water footprint performed by Mekonnen and Hoekstra in 2010. For the whole, dried larvae, the feeding substrate contributes 21 % to climate change impact, 62 % to terrestrial acidification impact, 79 % to freshwater eutrophication impact and 86 % to agricultural land occupation. For the same reason as explained above, the feed does not contribute to water depletion for whole dried larvae either.

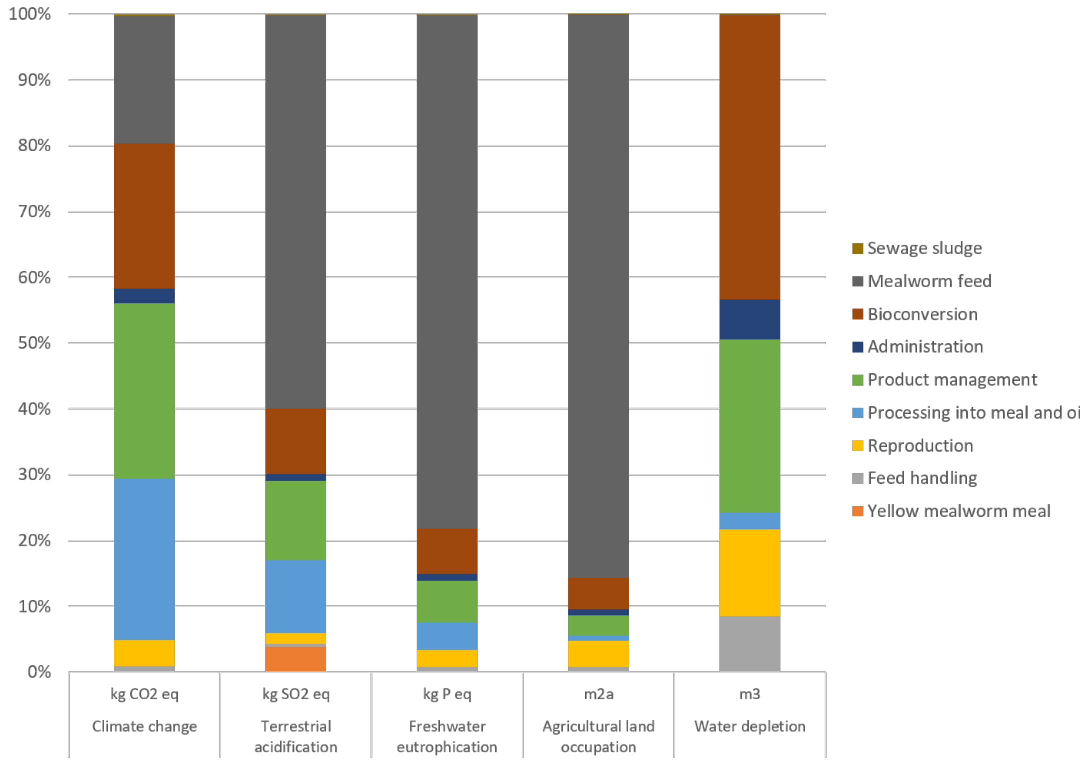


Figure 4.1: Contribution of the different production **stages** to the potential environmental impact for 1 kg of meal from yellow mealworm

Product management is another production stage which contributes noticeably to the environmental impacts for the yellow mealworm products. 27 % of climate change impact, 12 % of terrestrial acidification, 6 % of freshwater eutrophication and 26 % of water depletion is linked to product management for the production of yellow mealworm meal. Product management contributes the most of all the production stages to impact on climate change both for meal and whole, dried larvae. Also the bioconversion stage contributes largely to all impact categories for both meal and whole, dried larvae. This stage contributes the most to water depletion. A network analysis in SimaPro uncovered that this is caused by the large use of water for cleaning activities in addition to high electricity consumption for the climate system, which is indirectly connected to the use of water resources in terms of hydro power.

The processing stage also contributes notably to one of the impact categories, namely climate change. Processing the fresh, live larvae into marketable end-products contributes to 25 % of climate change impact for meal and 18 % for whole, dried larvae. This is primarily caused by heating in the drying process for both meal and whole, dried larvae, as uncovered by a network analysis in SimaPro.

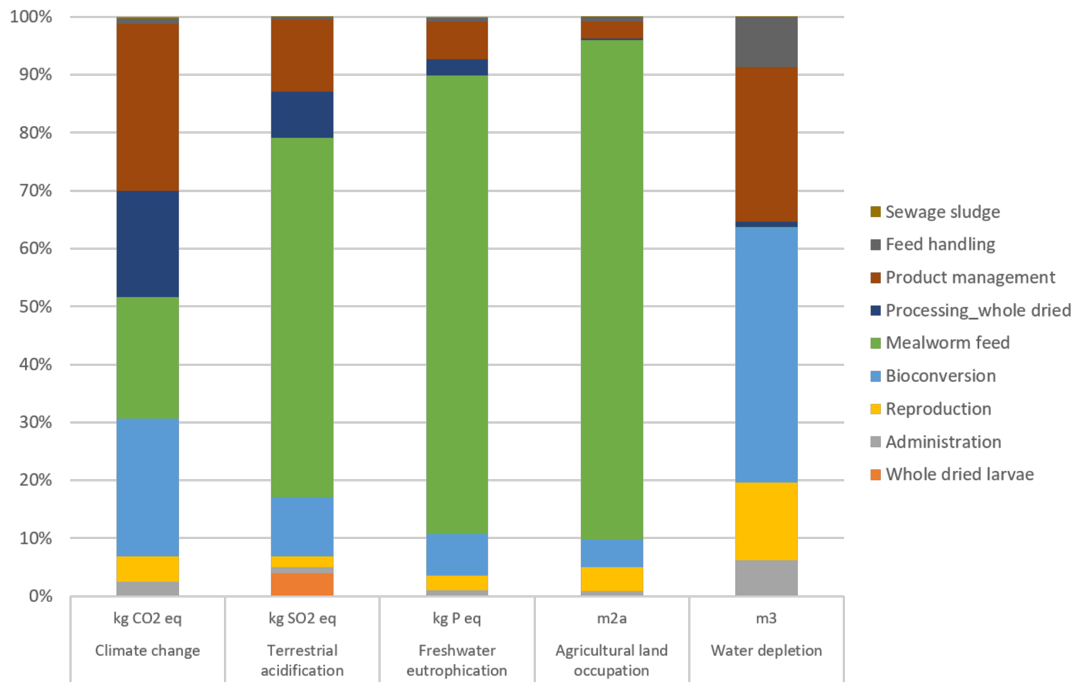


Figure 4.2: Contribution of the different production **stages** to the potential environmental impact for 1 kg of whole, dried larvae from yellow mealworm

4.1.2 Relative impacts of production processes

One of the research questions to be answered in this study is that of which of the production process(es) contribute(s) most to the environmental impacts from a Norwegian insect production system. The contribution of each of the modelled processing steps to the impact categories studied were therefore investigated. The results are visualized for each production process for the production of meal and whole, dried larvae in figure 4.3 and figure 4.4 respectively. These figures highlight the large impact associated with processes requiring heat, particularly for climate change impact. For both meal and whole, dried larvae, the heating of the product management facilities contributes notably, contributing 23 % and 25 %, respectively. The contribution from the feeding substrate is also notable in this category, followed by the heating of the insect production facilitates.

Based on the values given in table 3.3 it could be expected that heating the insect production facilities would have the largest impact, as this process has the largest heat requirement intensity (i.e. kWh/kg larvae) and also requires the highest temperature. However, total heat requirement for the heating of production management facilities is based on the total amount of finished products, i.e. the sum of meal, oil, whole, dried larvae and fertilizer. This is a substantially larger amount than the amount of fresh larvae which is the basis for the heat demand in the conversion process, and the heat demand for product management is thus higher, leading to a larger contribution from this processing step.Terrestrial acidification potential, freshwater eutrophication potential and agricultural land occupation are all dominated by the feeding substrate. Terrestrial acidification also shows significant contribution from heat-demanding processes such at heating of product management and insect production facilities as well as drying.

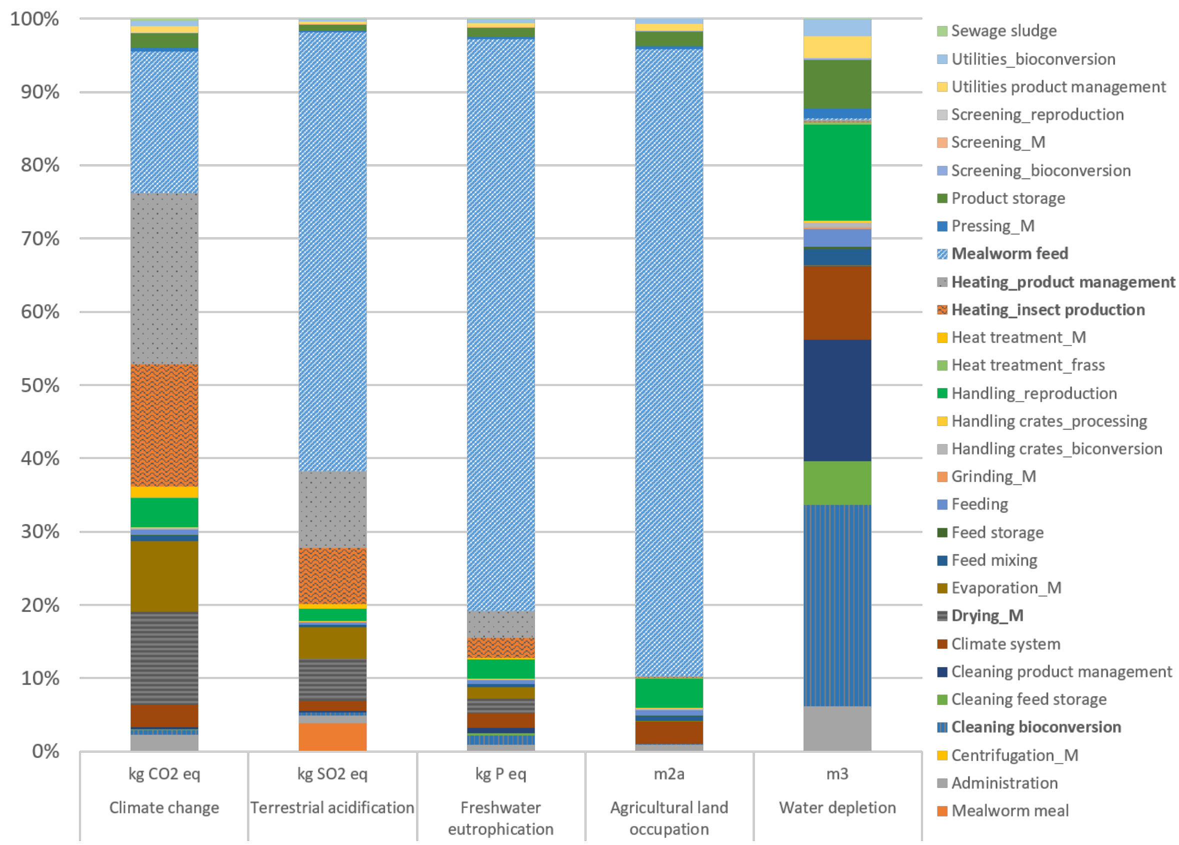


Figure 4.3: Contribution of the different production **processes** to the potential environmental impact for 1 kg of meal from yellow mealworm

4.2 Black soldier fly production

The total potential environmental impact for each of the six impact categories considered in this study for the production of black soldier fly larvae products can be seen in table 4.2. In this study the impacts from all of the production stages, i.e. feed handling, insect nursery, breeding and reproduction, processing, product management and administration have been distributed evenly between the products. For all stages except the processing stage, this reflect the real operational conditions. All products do not go through the same processing steps, which means that ideally impacts from the different processing steps should have been allocated to the different products according to the actual material flows to each individual process. However, this information was not available at the time of this study, and impacts from all processing steps were therefore allocated evenly between all end products. The relative contribution of each production stage and processes is therefore the same for all the products from the BSF production system.

The final impacts for each product in each impact category therefore reflects the economic allocation factors used to distribute the impacts, i.e. most of the burden allocated to meal, followed by oil and then puree. Even though oil is allocated substantially less of the impacts compared to meal, the impacts for oil in all categories are quite high. Similar to the yellow mealworm production system, this is caused by the relatively small amount of oil produced compared to the two other

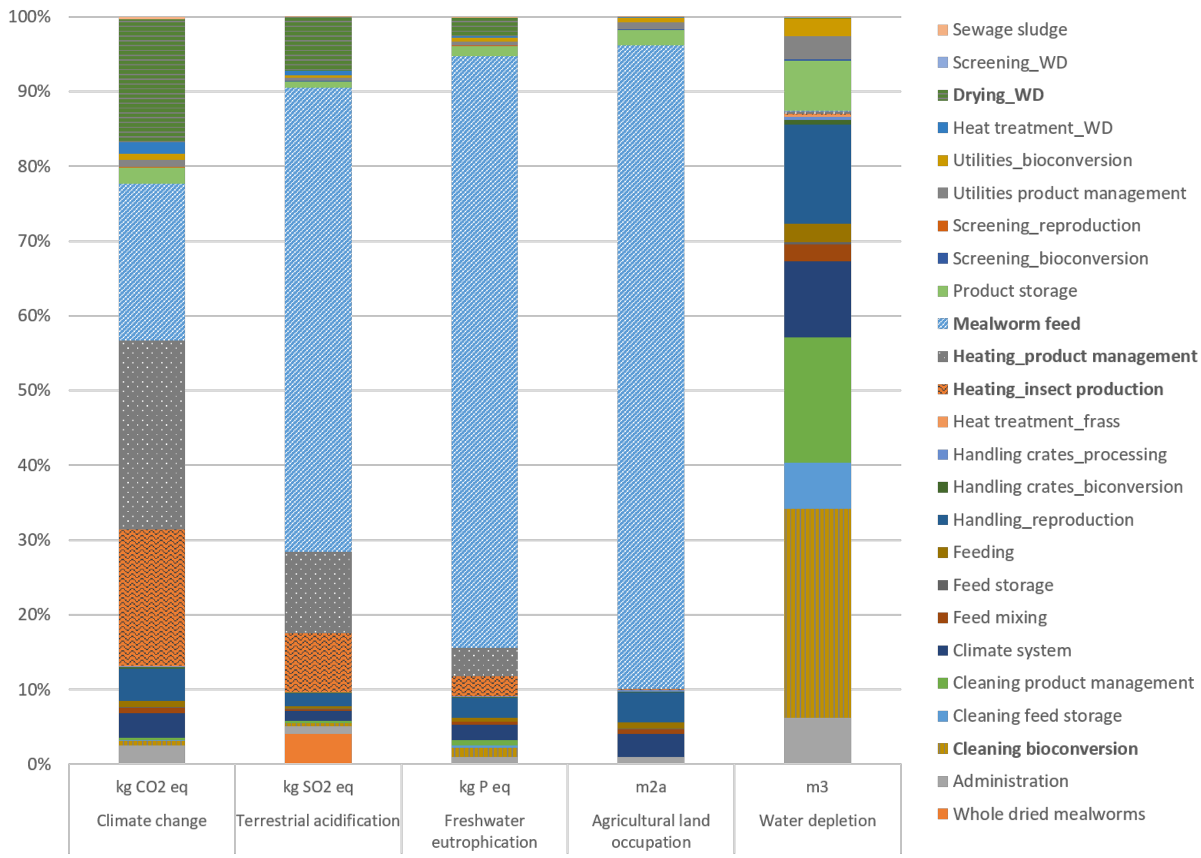


Figure 4.4: Contribution of the different production **processes** to the potential environmental impact for 1 kg of whole, dried larvae from yellow mealworm

products, which means that more resources and thereby also impacts are required to produce 1 kg of this product.

The cumulative energy demand for the BSF products follow the same pattern for the energy sources used for production as for the mealworms, due to input of the same resources to the system in terms of electricity mix and heat supply. For each of the BSF products, 58 % of the cumulative energy demand is supplied by non-renewable, fossil energy resources, 20 % is supplied by non-renewable, nuclear energy resources, 19 % is supplied by renewable water resources and 3 % is supplied by renewable biomass energy resources. The total non-renewable energy thus makes up 78 % of the total energy use.

4.2.1 Relative impacts of production stages

The relative contribution from each f the production stages to the total environmental impact in each category considered in this study is shown in figure 4.5. As the relative contribution of the different production stages to the final environmental impact in each category follows the same pattern for all the products, only meal is shown here. From the figure it can be seen that the feeding substrate given to the BSF larvae dominates the impacts in all categories except for water depletion. 66 % of climate change impact, 93 % of terrestrial acidification impact, 93 % of freshwater eutrophication

Table 4.2: Impact results for midpoint categories for products derived from BSF (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	Oil	Puree
Climate change	kg CO_2 eq	7.344	5.400	0.911
Terrestrial acidification	kg SO_2 eq	0.109	0.080	0.013
Freshwater eutrophication	kg P eq	0.005	0.004	0.001
Agricultural land occupation	m^2a	16.917	12.439	2.098
Water depletion	m^3	0.142	0.104	0.018
Cumulative energy demand	MJ	104.800	77.059	12.996

impact and 97 % of agricultural land occupation impact is contributed to the feeding substrate. Similar to the yellow mealworm production system, the high impacts associated with the feed are linked to the production of wheat bran.

The breeding and reproduction stage also contributes notably to climate change impact (15 % of total impact) and to water depletion (74 % of total impact). With regards to water depletion from the BSF production system, there is also a “negative” impact contribution from the wastewater treatment. This “negative” impact is linked to the recycling of water back to nature through wastewater treatment. The use of water for use in the production of BSF does as such not really deplete water, as most of the water is returned to its original state after being treated in a wastewater facility.

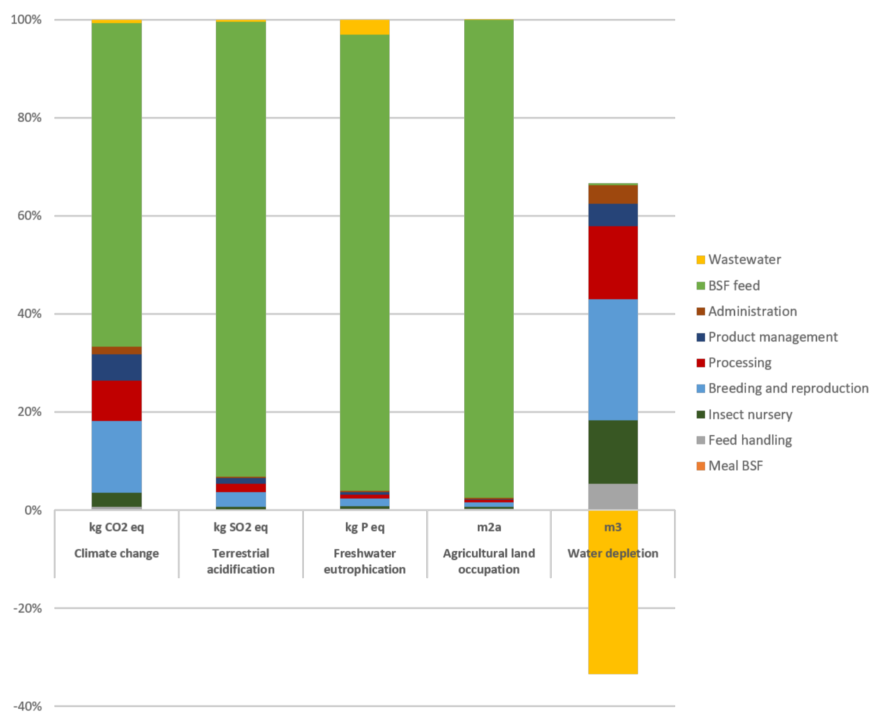


Figure 4.5: Contribution of the different production **stages** to the potential environmental impact for 1 kg of meal from BSF

4.2.2 Relative impacts of production processes

To gain better insight into which processes in the production is contributing the most to the environmental impact categories in this study, the relative contribution from each of the production processes is presented in figure 4.6. The same trends as was seen in figure 4.5 can be seen also in this figure, i.e. that feeding substrate still contributes the most to all impact categories except for water depletion, where wastewater is the most prominent contributor. However, this figure also illustrates the relatively large impact from heating processes. Heating of the rearing and breeding facilities represent 11 % of total climate change impacts and heat for the drying of products contributes 7 %. Heating of the product management facilities is also responsible for a notable share of 5 % of total climate change impacts for meal from the BSF.

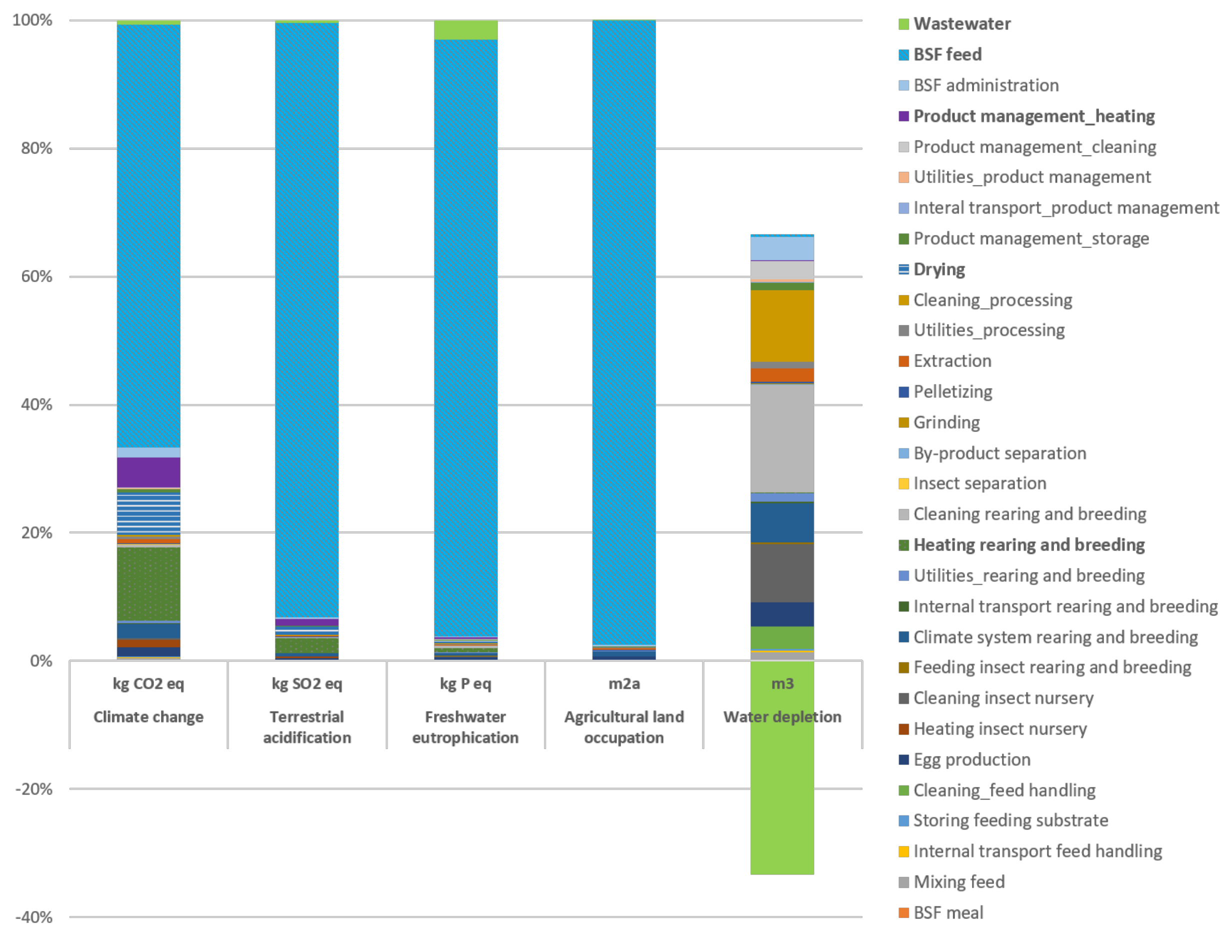


Figure 4.6: Contribution of the different production **processes** to the potential environmental impact for 1 kg of meal from BSF

4.3 Results for comparable production systems

The results obtained for soybean meal, rapeseed meal, palm oil and soybean oil from the use of generic processes in SimaPro is presented in table 4.3. Results for comparable products as obtained from Silva et al. (2018) is shown in table 4.4 and results obtained from de Vries and de Boer (2010) is presented in table 4.5. From table 4.5 it can be seen that no results were obtained for acidification and eutrophication potential. These impact categories were discussed by de Vries and de Boer, but no exact values were given, and it was considered to be too time-consuming to reproduce the results as presented in figure format in the study. The figure representing the range in the impact potentials obtained in these impact categories in the studies reviewed by de Vries and de Boer is therefore presented in figure 4.7 for reference in place of exact values. Finally, the results presented for chicken meat as a comparable product to the BSF puree is presented in table 4.6 based on values presented in Smetana et al. (2019). In the tables, YM is short for yellow mealworm.

Table 4.3: Impact results for midpoint categories for comparable products (ReCiPe Midpoint (H) and CED,FU 1 kg of product)

Impact category	Unit	Palm oil	Soybean oil	YM oil	BSF oil	Soybean meal	Rapeseed meal	BSF meal
Climate change	kg CO2 eq	4.440	4.499	13.081	5.400	2.525	0.928	7.344
Terrestrial acidification	kg SO2 eq	0.009	0.009	0.088	0.080	0.004	0.009	0.109
Freshwater eutrophication	kg P eq	0.000	0.001	0.003	0.004	0.001	0.000	0.005
Agricultural land occupation	m2a	1.625	8.822	10.051	12.439	2.731	2.001	16.917
Water depletion	m3	0.107	0.117	0.655	0.104	0.023	0.000	0.142
Cumulative energy demand	MJ	23.170	83.475	306.930	77.059	4.830	3.637	104.800

From table 4.3 it can be seen that the meal, i.e. the high-protein ingredients generally seem to be associated with lower environmental impacts than oils, i.e. the fat-rich ingredients. Similar to the trends observed for the insect products, this is most likely associated with the fact that these oils are by-products, and the total amount of these products are often much lower than the meals which they are a by-product from.

From table 4.4 it can be seen that the environmental impacts associated with fishmeal and fish oil produced from fisheries by-products are much higher than the impacts associated with the same products produced from Peruvian anchovy. This indicates the large variability in products which are often assumed to be the same, but which can have very different impacts depending on the production system. This implies that caution must be used when comparing environmental impacts from different products which seemingly fulfill the same function, but which are not necessarily the same.

Table 4.5 and figure 4.7 indicate that there are large variations in environmental impacts from

Table 4.4: Impact results for midpoint categories for comparable products from Silva et al. (2018) (CML-IA baseline V3.04, FU 1 kg of product)

		Silva et al. (2018)		*This study*	*Silva et al. (2018)*		*This study*	
Impact category	**Unit**	**Fishmeal from fisheries by-product**	**Fishmeal from Peruvian anchovy**	**BSF meal**	**Fish oil from fisheries by-products**	**Fish oil from Peruvian anchovy**	**BSF oil**	**YM oil**
Abiotic depletion (fossil fuels)	MJ	79.800	23.300	104.800	355.000	50.300	77.059	306.930
Acidification	kg SO2 eq	0.057	0.006	0.109	0.252	0.010	0.080	0.088
Eutropication	kg PO4 eq	0.016	0.001	0.005	0.072	0.002	0.004	0.003
Global warming	kg CO2 eq	5.370	1.310	7.344	23.900	2.190	5.400	13.081

Table 4.5: Impact results for midpoint categories for comparable products from de Vries and de Boer (2010) (FU 1 kg of product)

		de Vries and de Boer (2010)			*This study*	
Impact category	**Unit**	**Pork**	**Chicken**	**Beef**	**YM meal**	**Whole, dried YM**
Land use	m2	8.9 - 12.1	8.1 - 9.9	27 - 49	1.281	2.262
Fossil energy use	MJ	18 - 45	15 - 29	34 - 52	39.121 [CED]	64.744 [CED]
Climate change	kg CO2 eq	3.9 - 10	3.7 - 6.9	14 - 32	1.667	2.733

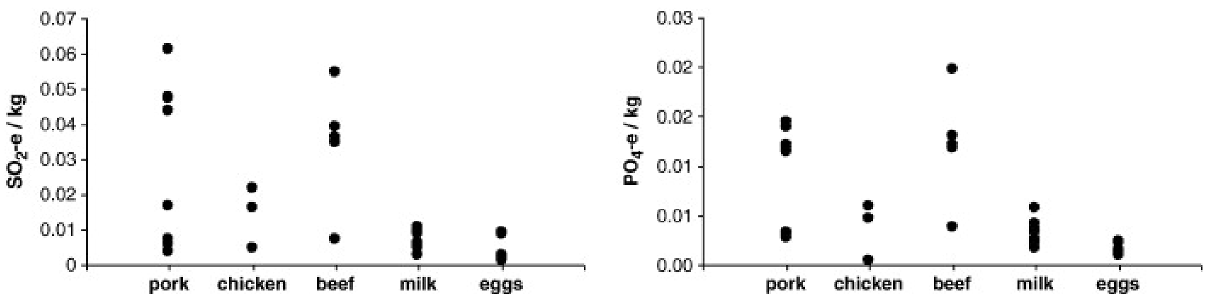


Figure 4.7: Acidification potential [kg SO_2-e] and eutrophication potential [kg $PO_4{}^{3-}$-e] for livestock products (FU 1 kg of product) from de Vries and de Boer (2010)

livestock products such as pork, chicken and beef. These variation are further highlighted if the impacts for chicken as reported in table 4.5 are compared to the impacts for chicken meat presented in table 4.6. Care should therefore be exercised when preforming comparisons of products, and these results can thus not be used to draw absolute conclusions about the environmental performance of different production systems.

Table 4.6: Impact results for midpoint categories for comparable products from Smetana et al. (2019) (FU 1 kg of product)

Impact category	**Global warming potential**	**Acidification**	**Eutrophication**	**Energy demand**	**Land use**	**Source**
Unit	kg CO2 eq	kg SO2 eq	g NO3 eq	MJ	m2 arable	
Fresh chicken meat	1.62 - 3.12	44.25	75	18.5 - 65	19.5 - 31.3	Smetana et al. (2019)
BSF puree	0.911	0.013	0.001 [kg P eq]	12.996	2.098	This study

Chapter 5

Sensitivity analysis

The results from this study indicate that the feeding substrate provided for the insects contributes notably to most of the impact categories considered. Energy use, particularly for heating purposes, was also shown to be an important environmental impact pathway in the systems examined here. A sensitivity analysis is therefore preformed to explore the sensitivity of the total environmental impacts in each of the chosen impact categories to changes in feeding substrate and energy supply solutions. Transportation activities were not included in this study, but is included as part of the sensitivity analysis as other studies have emphasized the contribution from this part of the value chain to the total impacts (Salomone et al., 2016).

5.1 Sensitivity scenarios

5.1.1 Feeding substrate

As of today, only vegetal resources are allowed as feed for insects. However, the interest and research efforts within the field of edible insects is increasing, and with an additional pre-treatment step to decontaminate food waste, also resources of animal origin might be allowed in the future. A sensitivity scenario was therefore created to investigate how the environmental performance of the system is affected by changing the feeding substrate from by-products and side-streams to actual waste streams.

Sensitivity scenario 1: Organic municipal household waste as feeding substrate

For the this sensitivity scenario, the use of organic household waste as feeding substrate for insects was modelled. The use of organic household waste is only assumed as feeding material for the BSF, as food waste from household generally is quite wet, making it unsuitable for the yellow mealworm. As the yellow mealworm only requires on the short side of 20 % of the incoming material to the system, it is assumed that they are given the same feeding substrate as in the main study, i.e. 3125 tons of spent brewer's grains, 1432 tons of food loss from the bakery industry and 756 tons of wheat bran.

The basis for this scenario is the use of organic waste from municipal households as feeding substrate for BSF, based on the collaboration between Invertapro and BIR, the local waste management company in Bergen on the West coast of Norway. BIR is not enforcing source separation of organic waste from residual waste in households today, but will have to introduce source separation of this fraction and ensure a suitable treatment option when this becomes mandatory by law in 2022 (Miljødirektoratet, 2018). As the residents within the BIR area do not source separate their organic waste today, there is no primary data representing what this will amount to. However, an estimate can be made based on the percentage of food waste from picking analysis preformed by BIR. According to the yearly report from BIR for 2017, 41 % of the residual waste fraction is food waste (including both loss and waste) (BIR AS, 2017). In the same report, a total amount of approximately 63 205 tons of the fraction residual waste was reported to have been collected by garbage trucks from households in the BIR area. Assuming perfect source separation, i.e. that all waste which can be categorized as food waste is source separated correctly into this fraction by the residents, this gives a total potential for the collection of 26 546 tons of organic household waste from this area. However, assuming perfect source separation is not realistic, and according to Sørgard (2018), only 49 % of waste which is food waste is actually source separated as food waste by residents in households in Norway. Using this as the premise for this study, a total of 12 973 tons of organic household waste is assumed to be collected by BIR from the residents in the Bergen area.

As discussed in section 2.5.3, pre-treatment of the feeding substrate is necessary if it originates from households. No such pre-treatment designed particularly for preparation of feed for insects exists today. To represent this step, pre-treatment similar to that used in anaerobic digestion facilities in Norway today is modelled as a proxy for this additional processing step in this study. The data is from a Norwegian research project mapping the environmental benefits of biogas production from food waste and manure, as described by Modahl et al. (2016). This processing step ensures that materials which are unsuitable as feeding substrate for insects, such as plastics, stone, and glass, are removed from the substrate. 7 % of the total incoming organic household waste is sorted out during the separation. This fraction is sent for incineration, as it contains materials which are not suitable as feeding substrate for insects (or for anaerobic degradation). This represents new technology, which fits well with this system. BIR does not have a facility for pre-treatment of food waste as of today, and must build this when implementing source separation of food waste.

The incineration of the sieving residues is also included in the inventory for this scenario. According to Modahl et al. (2016), an average composition of the sieving residue sent to incineration from pre-treatment of food waste consists of 99 % organic material, 0.82 % plastic, 0.07 % stone/inert material, 0.07 % textiles, 0.03 % glass and 0.03 % metal. A generic incineration process for biowaste from the Ecoinvent database was therefore used to represent this processing step. A detailed inventory for this process would have required an in-dept study of incineration technology and performance, which was considered to be outside the scope of this study. The Ecoinvent process is based on the incineration of average biowaste, consisting of a mixture of garden, yard and food/kitchen waste, which can be said to be an acceptable proxy for the sieving residues.

After the sieving residues have been sifted out in the pre-treatment step, water is added to the remaining material. As previously mentioned, this processing step is based on Modahl et al. (2016), which states that a ratio of 3.38 tons of water is added per 3.03 tons of incoming food waste, producing a total of 6.20 tons of pre-treated food waste. The water is added to achieve a dry matter content of 15 %, which is considered appropriate for best possible yield of methane, which is the desired product in an anaerobic digestion process. This ratio is based on the food waste having an original dry matter content of 33 %. Based on the desired moisture content in feed for BSF of between 70 and 90 %, a dry matter content of 15 % (corresponding to a moisture content of 85 %) is considered to be appropriate also for feeding substrate for BSF. This implies that the processing step of adding water to the feeding substrate and mixing the feeding substrate, which is presented in the inventory in table 3.2, is not necessary in this scenario, as water is added and the waste is mixed in the pre-treatment step. The pre-treatment step described by Modahl et al. (2016) does not contain any heat treatment step. This is necessary to ensure elimination of pathogens, and inventory data for this processing step was obtained from the pasteurization calculator provided in appendix 18 in the master thesis of Saxegård (2015). This master thesis is concerned with life cycle assessment of biogas production from organic waste sources in a Norwegian context, and data from this study is thus assumed to be representative for the pre-treatment step in this processing stage.

The inventory for the pre-treatment of municipal organic waste used in this scenario is shown in table 5.1. The pre-treatment is dimensioned to produce the exact amount of feeding substrate needed by the BSF, i.e. 24 688 tons per year. This requires an input of 12 065 tons of municipal organic waste (also referred to as food waste) per year, which is just short of the estimated availability of this resource in the BIR area. The required electricity per ton input of organic municipal waste is multiplied by the total input, i.e. 24 688 tons per year, to obtain the value of 189 960 kWh per year. Similarly, the heat requirement per ton input in multiplied with the total input, which gives a total heat requirement of 830 515 kWh per year. The food waste conversion factor is used to calculate how much food waste must be provided in to the system to be able to produce the desired final amount, and is taken from the material flow sheet presented in Modahl et al. (2016). The water consumption is also from the material flow sheet, and is used to estimate the total water requirement to produce the total desired output of pre-treated organic municipal waste, i.e. 24 688 tons per year.

Table 5.1: Inventory for the pre-treatment of municipal household waste, based on Modahl et al. (2016) and Saxegård (2015)

Input	**Amount**	**Unit**	**Amout for total production**	**Unit**	**Source**
Electricity	15.74	kWh/ton input	189 960	kWh/year	Modahl et al. (2016)
Heat	68.82	kWh/ton input	830 315	kWh/year	Saxegård (2015)
Food waste	0.498	ton input/ton output	12065	ton	Modahl et al. (2016)
Water	0.545	ton water/ton output	13459	ton	Modahl et al. (2016)
Output					
Sieving residues	7	% of input	845	ton	Modahl et al. (2016)
Pre-treated feeding substrate	1	ton	24 688	ton	This study

Similar to the allocation used for the food loss described in section 2.5.3, the organic municipal household waste used as feeding substrate in this scenario is not allocated any burden from the up-stream processes leading to the creation of this waste material. This allocation procedure is commonly used when modeling waste management of organic waste, and is implemented by both Salomone et al. (2016) and Mondello et al. (2017) in their studies on waste management practises for organic waste from households and the mass retail sector, respectively. In accordance with the cut-off allocation approach, this material is classified as a waste and not a by-product, meaning that the producer of this material is not given credits for producing a recyclable material.

An overview over the resources used as feeding substrate in this sensitivity scenario is summarized in table 5.2.

Table 5.2: Scenario 2: Organic municipal household waste

Feeding substrate	Amount	Unit	Comment
Brewer's spent grains	3125	tons/year	For mealworm
Food loss from bakery industry	1432	tons/year	For mealworm
Wheat bran to mealworm	756	tons/year	For mealworm
Organic municipal household waste	12065	tons/year	For BSF
Total	30000	tons/year	

5.1.2 Energy supply

Energy supply has been identified as one of the main environmental impact pathways of insect production systems, and different energy supply solutions are therefore investigated in the sensitivity analysis. It should be noted that the modelling of different energy systems has not been the main focus of this study, so these scenarios are based on existing processes from the Ecoinvent database without modifications. This increases the uncertainty of the results, as some of these processes are relatively generic, and represent for example an European average, or are based on data from one specific facility or geographic area. However, it was not possible to obtain case-specific data for these processes within the time-frame of this study, and the generic Ecoinvent processes were therefor used. This can be considered to be an acceptable uncertainty, as all other existing studies on insect production systems have also used generic processes from Ecoinvent as inventory for energy supply.

Sensitivity scenario 2: Electricity mix

In this sensitivity scenario, the electricity mix used as input to all processes requiring electricity was changed from Nordic electricity mix to European electricity mix. This corresponds to the system approach chosen by the ZEB Research Centre, i.e. in case studies of zero emission buildings in Norway (Fufa et al., 2016). In work performed in this field of research, the future development and integration of the European power grid is also considered. However, this is considered to be outside the scope of this study, and both the Nordic (NORDEL) and the European (ENTSO) electricity mixes are taken directly from the Ecoinvent database. The CO_2 emissions factors given in section 3.3.2 might therefore not correspond exactly to the electricity used in the Ecoinvent processes, but are useful to give an indication of the difference between the mixes.

Sensitivity scenario 3: Replacing district heating with local bio-energy production

An alternative to the use of electricity or district heating from a municipal waste incineration plant is to use local heat production from biomass. For an industrial sized insect factory as the one investigated in this study, the heating demand is so large that it could be reasonable to build an on-site local heating plant fueled on biomass. BKK, the local energy and infrastructure company in

Western Norway, is engaged in the provision of local thermal energy solutions. The use of biomass, which is a readily available resource in the area, could therefore be an option if the factory was to be established in an area without access to district heating. The relatively large impact from heat-demanding processes in this system also incentives the exploration of another heat supply option.

5.2 Transportation

5.2.1 Sensitivity scenario 4: Inclusion of transportation

In this sensitivity scenario, transportation activities were included for the feeding material provided for the insects to see how this affects the final environmental impacts for the production system. As mentioned in relation to the use of insect excreta as fertilizer, in Norway cereals are mainly cultivated on the East coast and in Trøndelag. Cereals such as wheat are therefore also usually milled in close proximity to where it is cultivated. The the statistic overview over Norwegian cereal production presented by the Norwegian Agriculture Agency, the Østfold region is highlighted as the largest producer of wheat in 2015 (Norwegian Agriculture Agency, n.d.[b]). In this region there also exists several mills, and wheat bran used as feeding substrate for the insects in this study is therefore assumed to be grown and milled here before being transported to Bergen. Map approximations give a total distance of around 570 km between Bergen and Østfold, which is used as total transportation distance for the wheat bran in this sensitivity scenario.

The food loss from bakeries and dairy production which is used as feeding material is assumed to originate from local companies, and an average transportation distance of 50 km is therefore assumed. The spent brewer's grains are assumed to be supplied by the local breweries, of which there are two large ones located within a 10 km radius of the industrial site in Rådalen. An average transportation distance of 10 km is therefore assumed for the brewer's grains. The transport is assumed to be done by lorry.

Transportation activities is calculated based on ton kilometre unit, which means that the total amount of tons of each of the feed ingredients was multiplied with the assumed transportation distance. The inventory used to model transportation of the feeding substrate in this sensitivity analysis is shown in table 5.3.

Table 5.3: Inventory for transportation in sensitivity scenario 4

Feeding substrate	Amount [tons]	Distance [km]	[tkm]
Yellow Mealworm			
Wheat bran	756	570	430 635
Food loss from bakery industry	1432	50	71 600
Brewer's spent grains	3125	10	31 250
BSF			
Food loss from dairy industry	7136	50	356 800
Wheat bran	17 552	570	10 004 355

5.3 Results from the sensitivity scenarios

5.3.1 Feeding substrate

Scenario 1: Organic municipal household waste as feeding substrate for BSF

The results for the sensitivity analysis involving the change of feeding substrate for the BSF from a combination of wheat bran and food loss from the diary industry to organic municipal household waste is shown in table 5.4. As previously mentioned, the final impacts to each category follows the same ratio for each product, so changing the inventory for the production processes produces the same relative changes for all three products.

Table 5.4: Impact results for midpoint categories for products derived from BSF in sensitivity scenario 1 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Puree	% change
Climate change	kg CO2 eq	2.718	-63%	1.999	-63%	0.337	-63%
Terrestrial acidification	kg SO2 eq	0.009	-92%	0.006	-92%	0.001	-92%
Freshwater eutrophication	kg P eq	0.000	-92%	0.000	-92%	0.000	-92%
Agricultural land occupation	m2a	0.414	-98%	0.304	-98%	0.051	-98%
Water depletion	m3	0.150	6%	0.110	6%	0.019	6%
Cumulative energy demand	MJ	78.212	-25%	57.509	-25%	9.699	-25%

From the table it can be seen that the impacts in all categories except water depletion is drastically reduced when the feeding substrate is changed from co-products to waste streams which are not allocated any environmental impact from up-stream activities. Water depletion is increased rather than decreased as a function of the additional water required in the pre-treatment step. The cumulative energy demand is not reduced as much as the impacts in the other categories, which emphasises the contribution of the other production processes to this particular impact category. This implies that the cumulative energy demand is not as sensitive to the feeding substrate as the other impact categories.

5.3.2 Energy supply

Scenario 2: Electricity mix

The final impacts in each impact category for the sensitivity scenario investigating the effect of the chosen electricity mix used as input for the insect production system are shown in tables 5.5 and 5.6 for the yellow mealworm and BSF respectively. From the tables it can be seen that environmental impacts associated with the production of yellow mealworm products is particularly sensitive to the electricity mix assumed as input to the system. The freshwater eutrophication impact associated with the yellow mealworm products is more than doubled when the electricity mix is changed from Nordic to European, which is caused by the increased use of fossil resources such as coal. Electricity production based on coal is common in many European countries, and is dependant on a mining process which often leads to eutrophication impacts on nearby water bodies.

Not all impact categories show increased impact potential when the electricity mix is changed, however. Both agricultural land occupation impacts and water depletion potential decreases. This is related to the fact that the European electricity mix introduces a different energy supply mix, which includes different natural inputs which replace land and water intensive resources such as hydro power and use of biomass for electricity generation.

The somewhat more modest relative changes observed for the products from the BSF compared to those observed for the yellow mealworm products are caused by the differences in the production systems. The yellow mealworm production system has an approximate 1:1.4 ratio between total electricity consumption and heat demand, as can be seen from the total electricity and heat demand shown in table 3.3. The BSF production system has a ratio closer to 1:1, which can be seen from the totals reported in table 3.2. The fact that the yellow mealworm products are more sensitive to the electricity mix than the BSF products is thus reasonable.

Table 5.5: Impact results for midpoint categories for products derived from yellow mealworm in sensitivity scenario 2 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Whole dried larvae	% change
Climate change	kg CO2 eq	2.801	68%	21.975	68%	4.672	71%
Terrestrial acidification	kg SO2 eq	0.016	39%	0.122	39%	0.027	39%
Freshwater eutrophication	kg P eq	0.001	237%	0.011	237%	0.002	232%
Agricultural land occupation	m2a	1.166	-9%	9.144	-9%	2.064	-9%
Water depletion	m3	0.055	-34%	0.434	-34%	0.097	-33%
Cumulative energy demand	MJ	49.808	27%	390.781	27%	83.028	28%

Table 5.6: Impact results for midpoint categories for products derived from BSF in sensitivity scenario 2 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Puree	% change
Climate change	kg CO2 eq	9.966	36%	7.328	36%	1.236	36%
Terrestrial acidification	kg SO2 eq	0.119	9%	0.087	9%	0.015	9%
Freshwater eutrophication	kg P eq	0.008	43%	0.006	43%	0.001	43%
Agricultural land occupation	m2a	16.649	-2%	12.242	-2%	2.065	-2%
Water depletion	m3	0.077	-46%	0.056	-46%	0.010	-46%
Cumulative energy demand	MJ	129.519	24%	95.235	24%	16.061	24%

Scenario 3: Replacing district heating with local bio-energy production

The sensitivity of environmental impacts for the different insect products to the heat supply assumed for the production processes was tested. The results for the yellow mealworm products are shown in table 5.7 and the results for the BSF products are shown in table 5.8.

The percent-wise changes given in the tables imply that there is a kind of trade-off from this change in heat supply. Climate change impacts and terrestrial acidification potential decreases for products from both insect production systems, while freshwater eutrophication potential, agricultural land occupation and cumulative energy demand increases. The changes are most prominent for the yellow mealworm products, while the BSF products are more moderately affected by the change. Agricultural land occupation is by far the impact category which is most sensitive to this change, which is reasonable given that using biomass as fuel for heat production requires

Table 5.7: Impact results for midpoint categories for products derived from yellow mealworm in sensitivity scenario 3 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Whole dried larvae	% change
Climate change	kg CO2 eq	0.659	-60%	5.172	-60%	1.140	-58%
Terrestrial acidification	kg SO2 eq	0.009	-16%	0.074	-16%	0.016	-15%
Freshwater eutrophication	kg P eq	0.000	7%	0.004	7%	0.001	6%
Agricultural land occupation	m2a	4.004	213%	31.415	213%	6.565	190%
Water depletion	m3	0.084	0%	0.657	0%	0.146	0%
Cumulative energy demand	MJ	43.148	10%	338.528	10%	71.108	10%

large areas to grow the biomass. The decrease in climate change impact and terrestrial acidification is explained by lower direct emissions from the burning of biomass compared to natural gas, and reduced impacts from mining associated with natural gas.

Table 5.8: Impact results for midpoint categories for products derived from yellow mealworm in sensitivity scenario 3 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Puree	% change
Climate change	kg CO2 eq	5.648	-23%	4.153	-23%	0.700	-23%
Terrestrial acidification	kg SO2 eq	0.106	-3%	0.078	-3%	0.013	-3%
Freshwater eutrophication	kg P eq	0.005	1%	0.004	1%	0.001	1%
Agricultural land occupation	m2a	21.497	27%	15.807	27%	2.666	27%
Water depletion	m3	0.142	0%	0.105	0%	0.018	0%
Cumulative energy demand	MJ	111.575	6%	82.041	6%	13.836	6%

5.3.3 Transportation

Scenario 4: Inclusion of transportation of feeding substrate

The results obtained for each of the products when transportation of the feeding substrate is included in the inventory is shown in table 5.9 for the yellow mealworm products and in table 5.10 for the BSF products. Table 5.9 shows that the total impacts are not significantly changed by the inclusion of transportation of feeding substrate for the yellow mealworm products. This is connected to the relatively large share of local feeding substrate used for the yellow mealworms, i.e. spent brewer's grains from local breweries and food loss from local bakeries. These supply chains involve short transport distances, and impacts from transportation is therefore not particularly large.

The BSF products on the other hand, are quite sensitive to the inclusion of the transportation stage as is shown in table 5.10. The impacts reported for most of the impact categories increased, except for agricultural land occupation. This is caused by the large share of wheat bran in the diet for the BSF, which must be transported over the longest distance. Combined with the fact that the total amount of wheat bran needed for the BSF production is much larger than for the yellow mealworm production due to that the total production amount of BSF larvae is notably larger than that of the yellow mealworm, it is reasonable that the BSF products are more sensitive to this transportation stage. The large increase in cumulative energy demand for the BSF products should

Table 5.9: Impact results for midpoint categories for products derived from yellow mealworm in sensitivity scenario (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Whole dried larvae	% change
Climate change	kg CO2 eq	1.845	11%	14.477	11%	3.048	12%
Terrestrial acidification	kg SO2 eq	0.012	6%	0.093	6%	0.020	7%
Freshwater eutrophication	kg P eq	0.000	3%	0.003	3%	0.001	3%
Agricultural land occupation	m2a	1.283	0%	10.070	0%	2.266	0%
Water depletion	m3	0.000	1%	0.002	1%	0.146	1%
Cumulative energy demand	MJ	42.015	7%	329.640	7%	69.883	8%

also be noted in this sensitivity scenario, which is caused by the extensive use of diesel as fuel in the lorry.

Table 5.10: Impact results for midpoint categories for products derived from the BSF in sensitivity scenario 4 (ReCiPe Midpoint (H) and CED, FU 1 kg of product)

Impact category	Unit	Meal	% change	Oil	% change	Puree	% change
Climate change	kg CO2 eq	12.274	67%	9.025	67%	1.522	67%
Terrestrial acidification	kg SO2 eq	0.128	18%	0.094	18%	0.016	18%
Freshwater eutrophication	kg P eq	0.006	9%	0.004	9%	0.001	9%
Agricultural land occupation	m2a	16.988	0%	12.492	0%	2.107	0%
Water depletion	m3	0.157	11%	0.116	11%	0.019	11%
Cumulative energy demand	MJ	183.979	76%	135.279	76%	22.815	76%

Chapter 6

Discussion

6.1 Main findings

This study has presented a range of potential environmental impacts which is associated with the production of insects in the Norwegian city of Bergen. The results obtained are in the range of impacts reported in other studies. Only two studies exist on the production of yellow mealworm (Oonincx and De Boer (2012) and Thévenot et al. (2018)), of which the first addresses the environmental impacts of fresh mealworm larvae, while the other both reports on the impacts associated with fresh live larvae and meal produced from euthanized mealworms. The impacts obtained for the yellow mealworm meal in this study are in the same order as those presented by Thévenot et al., but are generally a little lower. No studies exist on the environmental impacts of oil and whole, dried yellow larvae from the yellow mealworm, and the results obtained from these products are thus the first of its kind, to the author's knowledge.

For the black soldier fly (BSF), several studies exist on impacts from such production systems, of which the studies performed by Salomone et al. (2016), Rustad (2016), and Smetana et al. (2019) represent those which are most similar to the system modelled in this study. The results obtained for BSF meal by Salomone et al. are in the same range, but lower, than the results found in this study (for the comparable impact categories). This is somewhat unexpected, as the specific processes included in the two studies differ on some quite central elements. Salomone et al. included transportation of feeding substrate to the insect production facility, which contributed a notable amount to impacts, in addition to direct emission of GHGs from the BSF larvae. Lacking specific data on the direct GHG emissions from the BSF, another insect species was used as a proxy. The emissions modelled from that insect contributed massively to the global warming potential (expressed in terms of kg CO_2 eq) in the study by Salomone et al., which was confirmed in the sensitivity analysis. No direct GHG emissions were included in this study, which could have been though to induce large differences in the results obtained.

However, Salomone et al. used organic municipal household waste as feeding substrate for the BSF, and thus had no impacts from feeding substrate, which was found to be the largest impact pathway for the BSF products in this study. Considering the results obtained in sensitivity scenario 1 in this study this is confirmed, as these results are almost perfectly aligned with those obtained by Salomone et al. If transport has also been included in this study, the impacts would most likely not have particularly much higher in this study even if sensitivity scenario 4 indicated that the impacts for the BSF production system was particularly sensitive to transportation of the feeding material. This observation is deduced from the fact that organic municipal waste would originate from the municipalities near Bergen, and transportation distances would therefore not be as long as those modelled for the wheat bran. The results from this study can thus be said to be in agreement with the results obtained by Salomone et al.

On the other hand, the results obtained in this study are less comparable to the results obtained by Rustad (2016). Though both systems model the production of BSF in Bergen in Norway, very different datasets are used to model the environmental impacts from this type of system, and the results thus differ quite a lot. As an example, the impacts obtained in the climate change impact category for BSF meal in sensitivity scenario 1 in this study (which is the system most similar to that studied by Rustad) is more than ten times larger than the global warming potential presented by Rustad. This can most likely be explained by how the different production stages are modelled in these two studies. Where this study combines primary data and a detailed inventory from large-scale insect production from another study, Rustad did not have access to this kind of data and therefore had to rely on more generic Ecoinvent processes.

The fact that inventory used in this study is largely based on the inventory presented by Smetana et al. more or less predetermines the similarity of the results from these studies. The results in this study is in the same range as the results obtained by Smetana et al., but are generally a little higher in this study, except for the results for the puree, which are lower in this study. This is somewhat surprising, as the inventories are so similar, and if anything, the study by Smetana et al. (2019) includes more processes and production stages, which could have been though to inflict larger environmental impacts in place of lower. Another curious point is that one of the few differences between the studies is the electricity mix used as input. The Nordic electricity mix is generally assumed to have a lower environmental footprint than for example the Dutch electricity mix, which was used in the study by Smetana et al., and the impacts from the Norwegian system should by this logic be lower than those from the Dutch system. On the other hand, sensitivity scenario 2 in this study implied that the BSF production system is not very sensitive to the electricity mix used as input, and this should perhaps not be so surprising.

Something that might explain some of the differences observed between the results is that the Norwegian system is assumed to have a higher heating demand due to lower outdoor temperatures. By reason of heating processes being found to be one of the largest impact pathways for many of the impact categories, this might explain the higher impacts associated with the Norwegian system. There is also a difference in the data quality in the two studies. Smetana et al. obtained primary data over 1.5 year from an existing industrial scale insect production factory. This undoubtedly lowers the uncertainty and probably reduces the number of assumptions which have to be made to facilitate the modelling. One large source of uncertainty in this study is the allocation factors applied to distribute the environmental burdens to the different BSF products, as these had to be assumed. Smetana et al. on the other hand uses precise allocation factors based on prices obtained in the market for existing products, which might explain the higher impacts obtained for meal and oil in this study, while the results obtained for puree is lower than the results reported by Smetana et al.

All in all, the results obtained both for the yellow mealworm production and BSF production in this study agrees fairly well with the results found in the literature, and can thus be assumed to be representative. The results showed that feeding substrate and heating processes contribute most to the overall impacts, which indicate that special attention should be paid to these parameters when establishing insect production facilities its associated value chains in Norway. This will be further discussed here.

6.1.1 Feeding substrate

The results from the production of both yellow mealworm products and BSF products in this study showed that the production of the feeding substrate contributed most to the impact categories terrestrial acidification, freshwater eutrophication and agricultural land use and also notably to climate change impact. This confirms the results from other studies, in which the feeding substrate has been highlighted as a hotspot for environmental impacts to this kind of production systems (Halloran et al., 2016; Oonincx and De Boer, 2012; Thévenot et al., 2018; Smetana et al., 2019; Smetana et al., 2016). This was confirmed in the sensitivity analysis, where the feeding material for the BSF which was originally based on co-products (wheat bran) and side streams (food loss from dairy industry) was replaced by organic municipal household waste, which led to significant reduction in most most environmental impacts. Establishing a value chain for insect production which enables the use of waste streams as feeding substrate is thus of great importance when establishing a Norwegian insect industry.

However, one aspect of using waste streams as feeding substrate for insects which was not considered in this study is the fact that many waste streams, particularly those of organic composition, are beginning to gain status as a resource rather than an unwanted waste stream. This can be exemplified through organic municipal household waste, which is has traditionally been considered to be a nuisance, particularly after the prohibition on landfilling of organic waste in 2009. However, new value chains have been established to utilize this waste, and it is now extensively used as input for anaerobic digestion in Norway. From the anaerobic degradation process several useful products can be obtained, such as biofuel, electricity or heat, or a combination of these. If this organic waste stream is re-directed to insects, society will lose access to resources which are generally considered to be sustainable and which holds central positions in newly established value chains. The use of biofuel derived from anaerobic digestion is for example a key element in the Norwegian efforts to reduce environmental impacts from heavy road transport.

On the West coast of Norway, and in Bergen in particular, this is not a very large concern. This is mainly caused by the previously mentioned unsuitable conditions for using the bioresiduals from anaerobic digestion as fertilizer, and anaerobic digestion is thus not extensively widespread. In the Bergen area, there are currently limited available suitable alternatives to insect production for the organic waste fraction from households. This is connected to the implementation of circular economy principles with increased focus on material recovery of waste, which implies that organic waste must be sent for material recovery such as compost, anaerobic digestion or insect production rather than incineration.

It should however be mentioned that the insect frass, which is the the only "waste" product from insect production, has not been extensively tested as fertilizer yet. It might be possible that this material requires post-treatment through for example a composting process or in an anaerobic digestion process before it can be applied as fertilizer, which would probably increase the environmental impacts of the insect production system. This would also add another segment in the insect production value chain, and it might in such a case not necessarily be an improvement to anaerobic digestion as the same problem of this material being unsuitable for application on the farmland in this area of the country might arise. This has not been extensively researched yet, but is should be kept in mind when considering the effect on or in comparison to other value chains.

On the other hand, there is also the safety aspect of using organic waste streams as feed to consider. Even though the BSF larvae is capable of feeding on manure, this could potentially include safety risks for either humans or animals or both. Similarly, the knowledge of bioaccumulation effects of substances are not adequately known to allow any kind of material which could in theory be digested and upcycled by insects to actually be used as feeding substrate. The safety risks are quite simply not sufficiently understood at this point, and the regulations are therefore also very strict on the use of waste streams as feed for insects. This is also a symptom of the insect industry as a relatively new industry, in which the precautionary principle is predominantly applied because the effects could potentially be severe on human and animal health.

In the first phase, feeding substrates which are currently allowed by law must be used, i.e. vegetal resources which do not contain meat or fish. However, efforts should be made to find and utilize vegetal waste streams in place of, or in addition to, co-products such as wheat bran as this will undoubtedly reduce the environmental impacts of these system. In the case of large operations such as those modelled in this study where focus is put on utilizing waste streams, attention must also be paid to the potential need for additional processing stages, particularly for feed handling. If waste streams are used, there is a high probability that the volumes, consistency and quality of the waste received varies through the year. In this case, efforts must be made to ensure a homogeneous composition of the feeding substrate, and to pursue a relatively similar nutrient composition at all times to assure stable production of high-quality products. This might demand extra buffer capacity in terms of for example freezers to preserve feeding substrate for later use, which would induce a higher energy demand, which could potentially increase environmental impacts.

6.1.2 Energy supply

The results obtained in this study identified heating as one of the main environmental impact pathways both for the production of yellow mealworm and BSF, which highlight the importance of designing the insect production facility so that it can use the heat provided as efficiently as possible. In this study, the contribution of the heating of rearing facilities was emphasised, which confirms the trends observed in other studies (Halloran et al., 2016; Oonincx and De Boer, 2012). However, the relatively high impact associated with heating of product management facilities, including storage of products, is somewhat new. To some degree this reflects the relatively cold climate in Norway, and thus a larger heating demand for a larger period of the year. However, this might also illustrate that modelling of this production stage is not entirely optimal in this study. To find the heat demand for this stage, the heat demand per kg of product as given in Smetana et al. (2019) was used, assuming that all products were stored under the same conditions. This assumption might have led to an unreasonably high heat demand for this stage, as no information of what conditions the product management facilities are operated under were obtained in this study. Additionally, the use of degree days to estimate heating demand in Norway relative to heating demand in the Netherlands led to a relatively large increase in the heat demand per kg product, which might also have augmented the contribution from this production stage. Caution should therefore be used when interpreting these results.

Similar caution should be applied specifically for interpretation of the yellow mealworm production system. A cell-based rearing system was modelled in this study, but as no available data exists for the energy use of this system, data from the BSF production system described by Smetana et al. (2019) was used. The energy efficiency gains which could potentially be obtained from the cell-based system in terms of these small closed production units which limit heat leakages to other processes was therefore not observed in this system. This design for yellow mealworm production offers detailed environmental control of each separate production cell, which could potentially enable targeted utilization of the metabolic heat produced by the mealworms, which would lower the heat demand for each individual cell, in particular in the phases of the larval stage where the larvae produce the most metabolic heat.

In addition to how the heating of facilities is modelled, the impacts are dependent on the external heat supply used to deliver the heat. Using natural gas as proxy for waste heat from waste incineration facility as done in this study introduces impacts to the use of heat which should not technically be allocated to this heat. The product declaration for the heat produced from the municipal waste incineration in Rådalen presets two methods for calculating the CO_2 intensity of this heat. The method which draws a parallel to natural gas does technically only refer to the direct emissions from the incineration of natural gas as a proxy for the incineration of waste, rather than the whole upstream supply chain involved in producing the heat. In this study, natural gas was used in place of waste heat from a municipal waste incineration facility, which means that upstream impacts from for example the extraction of natural gas, as well as the transport of this gas, is included. This is not an accurate representation of the upstream supply chain for the burning municipal waste, and the impacts from this assumptions might therefore be unreasonably high in this study.

On the other hand, sensitivity scenario 3 showed only moderate reductions in environmental impacts if the heat supply waste changed to a local biomass solution, especially for the BSF system. The yellow mealworm products showed large reduction in climate change impacts in this sensitivity scenario, but at the same time the agricultural land occupation increased drastically. This indicates that different heat production technologies might offer trade-offs in terms of environmental impacts. To further investigate the effects of different energy supply solutions a separate study where a larger range of different energy systems are investigated. The results in this study cannot facilitate any recommendation on what kind of energy supply systems are preferable for use in Norwegian insect production systems, as the systems investigated in this study are very generic and presents a very limited selection of possible solutions. The results presented in this study only highlight that the choice of heat supply system has a notable impact on the total environmental impacts, and should therefore be properly considered when new production facilities are designed and built. It should also be mentioned that when a completely new factory is built, a combination of energy solutions can be utilized based on locally available resources and the specific requirements of the factory. Such a tailor-made system can reasonably be expected for an industry such as this, where sustainability, low environmental impacts and local solutions are emphasised.

6.2 Comparison to benchmark products

As mentioned in section 2.3, comparing results across studies is complicated for insect production systems because of differences in the methods used, functional units, system boundaries and allocation procedures. This also applies to other food and feed production systems, and the variations in the methodological frameworks applied are even larger, as there exists even more studies on such production systems than for insect production systems. Though the variations are large, and no absolute conclusions can be drawn, some observations can be made.

Starting with the feed ingredients, i.e. the BSF meal, the yellow mealworm oil and the BSF oil, from the comparable products presented in section 4.3 it can be seen that the environmental impacts (represented by the impact categories used in this study) for insect-derived products are generally a little higher than its comparable products, particularly compared to plant-based alternatives. Yellow mealworm oil seems to have higher impacts than both palm oil and soybean oil in all impact categories considered except for water depletion. The BSF oil also has higher impacts than palm oil but seem to show quite similar, if only a little higher, impacts than soybean oil. The impacts associated with fish oil depends on the source of the raw-material. If compared to the fish oil from by-products from fisheries, both yellow mealworm oil and BSF oil seem to have lower impacts in all categories, while the opposite is true if compared to fish meal from Peruvian anchovy. Similar trends can be observed for the BSF meal in comparison to the plant based alternatives. BSF meal seems to have higher impacts in all categories than both rapeseed meal and soybean meal. However, when BSF meal is compared to fish meal, both from by-products from fisheries and from Peruvian anchovy, the BSF meal has the highest impacts in all categories for both comparisons.

For the oil products these results generally confirm the trends observed by Smetana et al. (2019) in which insect products are not entirely competitive with its plant-based feed ingredient alternatives with respect to environmental impacts, but are more or less comparable to animal products such as fish oil. The BSF meal, on the other hand, had significantly higher impacts in all categories compared to fish meal, which from an environmental perspective makes it less competitive. In these consideration one must make note of the fundamental differences in these systems. The production of fish meal and fish oil are based on essentially “free” resources, as there is no need for extensive input of water, land or energy to facilitate production, as these are a natural part of the habitat of the fish. Some additional inputs are necessary for processing the fish into final products, but these inputs are relatively small. Though the production of fish meal does not necessarily have large impacts on the environmental impact categories presented in this study, fish meal and oil production is know for large contribution to for example biodiversity loss. It should therefore not be concluded that the BSF meal is not viable for use in feed based only on its comparison to other ingredients in a limited number of impact categories.

This raises the point of how impact categories are weighed against each other. For example, in the study of aquafeed ingredients by Silva et al. (2018), fish oil from fisheries by-products is reported to have relatively high impacts, which can be seen in table 4.4, while one of its potential alternatives, soybean oil, has relatively low impacts. This could be used to argued for soybean oil as a more preferable aquafeed ingredient from an environmental point of view. However, in this study land use was not considered, an impact category in which soybean products often have high impacts. The question of which impact categories should be used as basis for comparison, and in cases where there is no clear “better” alternative is therefore an important one. A solution to this is to use endpoint impact categories, where the results in the impact categories are aggregated into a few endpoint categories. This method is used in Smetana et al. (2016) and Smetana et al. (2019), and can be argued to provide a better foundation for comparison of products such as the insect products investigated in this study.

Comparing the insect products intended for human consumption with other high-protein animal products, the results obtained for land use and climate change impact are lower for both yellow mealworm meal, whole dried mealworm larvae and the BSF puree than their comparable products. With regards to energy use, both yellow mealworm meal and whole dried larvae show impacts in the high range of their livestock alternatives, but the energy use reported for the insect products include both renewable and non-renewable energy resources, while the values reported for pork, chicken and beef only include fossil resources. The BSF puree was allocated very little of the environmental burden from the production of the BSF, and has substantially lower impacts in all categories compared to fresh chicken meat. Based on these observations it seems that insect products for human consumption are favourable to the animal products considered here from an environmental point of view. No definite conclusions can be made based on these observations, but the comparisons provides a useful context for discussion.

By way of comparison, the direct consumption of insects provide larger environmental benefits than the use of insects as feed for animals. This is reasonable when considering that feeding insects to for example fish adds another level in the food chain compared to the direct consumption of the same insects. From a wider perspective, prioritizing insects as food for people rather than animals is also more reasonable based on economical considerations. When insects are used as feed, they must also be economically competitive to other feed ingredients, which is in a much lower price range than animal proteins for human consumption. Establishing insects as food commodity could therefore help accelerate the establishment of the insect sector, as the products could be sold for larger profit and also generally seem to have lower environmental impacts than other high-protein products such as beef, pork and chicken.

On the other hand, it can also be argued that not all insect species are favourable for human consumption, and diversifying to supply different markets could therefore be considered to be a strength of the insect industry. Some insects simply are not particularly palatable for humans, such as the BSF, while others are winged or scaled, such as the grasshopper, which make it less comparable to other animal protein sources. The novelty of insects as food in Western cultures must also be considered, which is a notable barrier to the fast development of the insect sector. Insects have not been extensively present in Western diets, and is commonly associated with disgust or fear. Using insects as feed for animals which are subsequently eaten by humans might therefore be a suitable strategy to “ease” European consumers into acceptance of this new food commodity. This is also fitting with the actual demand existing for insects in Norway today. While the Norwegian aquaculture has explicitly stated their interest in using insects as a feed ingredient in aquafeed, the same interest can not be said to exist from Norwegian consumers, even though many are curious to try.

Many advocate for insects as a sustainable alternative in both feed and food formulations, and insects have been highlighted as on of the important “new” protein sources for a more sustainable future. Insects undoubtedly have characteristics which could enable this, but the question of how sustainable these resources are, is more nuanced. An LCA, such as the one performed in this study, does not fully reflect all parameters which are relevant when comparisons are made. Even though insects may not be environmentally favourable to plant-based alternatives such as products derived from soybeans, insects can be more favourable in other aspects. In this study, insect feed products were only compared to other feed ingredients before their use as feed, and the actual nutritional effects of the different feed were as such not considered. Plant-based feed ingredient for fish have are commonly associated with poorer fish development due to unfavourable nutritional factors, which can lead to lower production volumes and quality of the fish produced and subsequent lower profitability of the fish (Silva et al., 2018). Taking this into consideration, the somewhat higher environmental impacts associated with insect-derived feed ingredients might be an acceptable trade-off, as it could potentially lead to higher productivity and quality in downstream applications of these feed ingredients.

This highlights the uncertainty of comparing products only based on mass, i.e. comparing the environmental impacts from one kilo of one product to one kilo of another product, without regard for other parameters such as nutritional qualities or economic value. The need for more comprehensive analyses, and also including down-stream impacts are thus required to enable truly fair comparison between products. These considerations are also valid when comparing products in terms of sustainability, as caution should be applied with reference to the use of the world sustainable to characterize and compare products. Sustainability encompasses more than just the environmental impacts of a product, and to claim that some products are more sustainable than others only based on environmental impacts is not entirely fair. To fully explore the concept of insects as a sustainable source of animal protein, more extensive analyses must be performed, also including economical and social aspect of the production.

6.3 Strengths and weaknesses

As briefly discussed above, the dual production of insect products for both food and feed markets can be considered to be a strength of this study, due to the flexibility this presents for an industry which is currently working to establish itself. This also represents the real life plans of the existing collaboration between Invertapro and BIR, which further emphasises the relevance of this modelling choice. On the other hand, modelling two production systems for insects in this study provided challenges as data is not readily available at the desired level of detail for all production processes. This resulted in the application of a large number of assumptions, which significantly increased the uncertainty of the results found in this study.

This applies particularly to the modelling of the production system for the yellow mealworm. Even though primary data was obtained from the designers of the system modelled, not all relevant data was possible to obtain, which among other things resulted in the use of data for production of the BSF as a proxy for the heat demand in the rearing facilities for yellow mealworm. As already mentioned, this is a large source of uncertainty in this study, as the system modelled for yellow mealworm production is designed specifically to address the use of heat and the adaption of environmental conditions to different stages of the insects reared. Even though the quality of the data used to model the yellow mealworm production is not as high as desired, this study still represents a significant contribution to the research field of the environmental impacts associated with insect production, as no other detailed inventory for yellow mealworm production exists in the literature today. Efforts were also made to model the use of automated technology, which is a crucial factor for the successfully upscaling and establishment of the insect sector. This can be viewed as a strength of this study.

With regards to the goal and aims set for this study, one of the main purposes of this study was to model insect production specifically in a Norwegian context. This was achieved to some extent, by modeling the utilization of locally available feeding substrates and energy sources. However, production parameters such a Norwegian climate was more difficult to properly integrate in the study due to limited data availability. Assumptions were therefore applied to extrapolate process parameters from production in the Netherlands to Norwegian production conditions. As heating processes were found to be one of the main contributions to environmental impacts in this study, second only to the feeding substrate, this is a prominent weakness of this study which increases the uncertainties associated with the results and the interpretation thereof.

Other modelling choices made in this study also contributes to increasing the uncertainty of the results. This pertains particularly to the choice of functional unit. A mass-based unit was chosen in this study, but as mentioned above, this limits the use of comparisons to other food and feed commodities, as other qualities of the products are not given any consideration. Only using one functional unit is also in opposition to the guidelines for insects LCAs provided by Halloran et al. (2016), where the importance of using at least two functional units was emphasised. This limitation is also valid with respect to the allocation method used in this study. By using economic allocation, the impacts are distributed according to the relative value of the products.

However, data on the exact value of these products are incomplete, particularly for the BSF products in this study as no Norwegian company produces this insect as of today and the value of these products in the Norwegian market is therefore difficult to predict. Data from other companies which are producing the BSF in other European countries are also inaccessible, as the insect industry is in rapid development, and any element representing a possible competitive edge is typically undisclosed. The use of economic allocation can thus be said to be weak modelling choice, and for example energy content would possibly have been better as this can be measured and is not dependant on the market situation or data availability. Energy content could also be argued to better represent the property of insects which makes it valuable for food and feed purposes.

6.4 Implications of findings and future work

This study is the first to include a detailed inventory of large-scale production of the yellow mealworm, and also the first addressing the combined production of two different insect species at the same site. Oonincx and De Boer (2012) studied the production of both yellow mealworm and superworm, but these two insects are of the same species (*tenebrionids*), and have similar life cycles and require the same type of feeding substrate and environmental conditions, and are thus considered to be the same for the purposes of the study.

The results from this study represents the joint plans of Invertapro and BIR in Bergen in Norway, and can be used to assess which production parameters have large influence on the potential environmental impacts of such production systems in a Norwegian context. The most crucial parameters, which were found to be the feeding substrate and heating of production facilities in this study, should be paid special attention when such large-scale production facilities are designed and implemented. However, even though the production of yellow mealworms and BSF were modelled in this study, they were modelled separately. Such systems as this could potentially benefit from industrial symbiosis, i.e. exchange of waste flows from one system for use as a raw material in another. The potential for industrial symbiosis in insect production systems was to some extent explored by Wang et al. (2017), but this study focused on the use of the yellow mealworm and the BSF for biodiesel production rather than for feed and food purposes. Investigating possible symbiosis effects in insect production systems as the ones explored in this study could potentially highlight how resources could be more efficiently utilized and thus also alleviate the circular concept embodied in inset production.

This study also highlights the need for available, high quality data for the individual production processes in an insect production facility. Many assumptions and simplifications had to be made to facilitate this study, and for the further development within this field, more open-access data sharing could benefit the whole insect industry. Such data availability would enable early-phase LCAs of insect production in specific contexts to guide technology choices and system design when establishing new factories. Using representative data for full-scale automated production of insects to create a detailed life cycle inventory should thus be a priority.

In future studies, emphasis should also be put on incorporating a more comprehensive understanding of the potential embodied in insect production through the use of different functional units and allocation procedures. The functional unit largely predetermines the possible interpretation of results obtained in an LCA and also frame the discussion on comparable systems or products. The economic value of products is commonly used as basis for allocation procedures in LCAs, and is often a representative indicator for demand in real markets. However, in multi-functional production systems such as insect production, products might end up in different markets, and the relative difference in economic value might therefore not be an appropriate indicator.

This can be exemplified by the fertilizer product produced from insect production. Fertilizer products are sold in at a price of 0.5 % of the price of insect meal (Salomone et al., 2016), which in an allocation procedure based on economic value would mean that no essentially no impacts are associated with this product. This would lead to insect fertilizer being seemingly very environmentally favourable compared to for example mineral fertilizer. However, compared to the prices of other fertilizer products, insect fertilizer products might be in the higher range of price, as it is a relatively new.

This is also relevant with regards to the allocation procedures applied for up-stream impacts of insect systems. As an example, the use of by-products, side-streams and waste as feeding substrate for insects, and in alternative applications of these resources raises the question of applying appropriate allocation rules. Some by-products and side-streams have economical values, while others do not, and for waste streams such as household waste, these resources do in many cases have a negative economic value, i.e. that those who posses this resource must pay for it to be handled down-stream. The value of different resources is thus about to change with the transition to a more circular economy, and efforts should be made to incorporate this into studies on environmental impacts.

The use of LCA as a tool for assessing the environmental performance of insect production systems could also be discussed with respect to the relevance of the results and implication for the growth of the insect industry. LCA is a tool aimed a tracking the environmental impacts through the whole life cycle of products and services. For a single product or a particular service, this approach can provide valuable insight, but as seen in this study, there are many uncertainties associated with LCA modelling of a multi-functional systems. There are also challenges associated with incorporating all the relevant aspects of insect production into an LCA, such as the use of waste resources as input, or the performance and consumer acceptance of the end products.

It is also important to keep in mind that LCAs are limited to providing insight into the environmental aspects of insect production, and other aspects which are relevant for drawing conclusions on the overall sustainability of insect production such as economical and social viability is thus not assessed. Efforts should therefore be made to develop tools for a more wholesome assessment framework which enables better representation and interpretation of these kinds of systems.

With regards to the Norwegian insect production sector in particular, future studies should explore the possible waste management services which can be performed by insects. Efforts should be made to map resources which are suitable as feeding substrate to insects and which are also available in Norway. Mapping should include both resources which are allowed as feeding substrate for insects within the existing regulatory framework, and also alternative an innovative resources. To facilitate this approach to insect production, the effect of different types of feeding substrate on growth, health and development on different insect species is also needed.

Chapter 7

Conclusion

The results presented in this study give a preliminary indication of potential environmental impacts associated with insect production based on Norwegian resources and production considerations. A joint industrial scale production of the yellow mealworm and the black soldier fly in Bergen on the West coast of Norway was modelled. The results identified the feeding substrate provided for the insects as well as the process of maintaining high indoor temperature to facilitate the growth of the insects as the parameters which contribute the most to environmental impacts associated with this production system.

This implies that special attention should be given to the heat supply solution chosen when the production facilities are designed, and that efforts should be made to ensure heat recovery and utilization of the “free” metabolic heat produced by the insects in their larval stage. Establishing value chains that facilitate the use of resources which have little or no utility value as feeding substrate for insects should also be a priority to ensure the lowest possible environmental impacts from this system. When such value chains are established, efforts should be made to utilize locally available materials, to further lower impacts associated with transport. The collaboration between Invertapro and BIR can thus be considered to be a strategic partnership which enables this approach to insect production in Norway.

However, the study also highlights that the modelling of large-scale insect production in Norway when no such facilities currently exist from which primary data can be obtained presents some methodical challenges. The results can still be used to provide valuable insight into the most important impact pathways of such a system, but no definitive conclusions can be made. The results can thus be interpreted to present more of an indication rather than absolute values for the impact categories investigated.

These considerations also reflect the comparisons made between insect-derived products in this study and other products for use in either food or feed. This study indicated that insect products intended for human consumption, such as meal, whole dried insects and puree, have lower environmental impacts than the animal products used for reference. This can be attributed to the high feed conversion efficiency of the insects, in addition to their low direct emissions of GHGs, as well as the possibility of farming insects vertically with little use of water.

On the other hand, insects were not found to be significantly better than other feed ingredients with respect to environmental impacts, and even had notably higher impacts in some cases. This can be explained by the additional level added to the food chain by introducing insects as feed for the animals eventually eaten by humans rather than the direct use of insects as human food. The potential environmental benefits of insects as feed which has been highlighted by others was thus not reflected in this study, but should not be entirely eliminated only based on this study. As was discussed in this study, different feed production systems rely on different resources and subsequently have different impact patterns, which is not always clear from the results obtained in LCAs.

It can be concluded that insects clearly have characteristics which make protein production from this animal an interesting solution with respect to the increasing population and consequent need for food and feed. It is clear that new production systems which ensure better resource utilization and have lower impacts on the ecosystem services on which we depend must be developed for a sustainable future, and the production of insects can most certainly be one such production system. Insect production also holds potential specifically in Norway, as the demand for alternative protein sources in aquafeed is considerable.

Bibliography

Agriprotein (n.d.). *Fly-farming*. `https://agriprotein.com/press-office/fly-farming/`. Accessed April 12th, 2019.

Andersen, Jonas Lembcke (2019). Personal communication. Specialist at the Danish Technological Institute with knowledge on the biological requirements, and the optimization of these, for insects reared for feed and food.

Andersen, Jonas Lembcke and Ida Berggren (2017). *Brugsanvisning Tenebrio molitor æggesamler*.

Andersen, Otto, Torunn Gauteplass Hønsi, and Gunnhild Jaastad (2017). "Lokale kjelder for proteinfôr til husdyr og fiskeoppdrett på Vestlandet". In:

Banks, Ian John (2014). "To assess the impact of black soldier fly (Hermetia illucens) larvae on faecal reduction in pit latrines". PhD thesis. London School of Hygiene & Tropical Medicine.

Barry, Tami (2004). "Evaluation of the Economic, Social, and Biological Feasibility of Bioconverting Food Wastes with the Black Soldier Fly (Hermetia illucens)". PhD thesis. University of North Texas.

Belghit, Ikram, Nina S Liland, Rune Waagbø, Irene Biancarosa, Nicole Pelusio, Yanxian Li, Åshild Krogdahl, and Erik-Jan Lock (2018). "Potential of insect-based diets for Atlantic salmon (Salmo salar)". In: *Aquaculture* 491, pp. 72–81.

Benzertiha, Abdelbasset, Bartosz Kierończyk, Mateusz Rawski, Paweł Kołodziejski, Magdalena Bryszak, and Damian Józefiak (2019). "Insect Oil as An Alternative to Palm Oil and Poultry Fat in Broiler Chicken Nutrition". In: *Animals* 9.3, p. 116.

BIR AS (2017). *BIR årsraaport 2017*. `https://bir.no/media/1573/aarsrapporten-2017.pdf`. Accessed May 30, 2019.

BizEE Software (n.d.). *Custom Degree Day Data*. `https://www.degreedays.net/`. Accessed May 30th, 2019.

Boissy, Joachim, Joël Aubin, Abdeljalil Drissi, Hayo MG van der Werf, Gordon J Bell, and Sadasivam J Kaushik (2011). "Environmental impacts of plant-based salmonid diets at feed and farm scales". In: *Aquaculture* 321.1-2, pp. 61–70.

Broekhoven, Sarah van (2015). "Quality and safety aspects of mealworms as human food". PhD thesis. Wageningen Universiteit.

BV, Blonk Agri Footprint (2015). "Agri-footprint 2.0–Part 1: Methodology and Basic Principles". In: *Netherlands: Gravin Beatrixstraat* 34, p. 2805.

Cheng, Jack YK, Sam LH Chiu, and Irene MC Lo (2017). “Effects of moisture content of food waste on residue separation, larval growth and larval survival in black soldier fly bioconversion”. In: *Waste management* 67, pp. 315–323.

Chia, Shaphan Yong, Chrysantus Mbi Tanga, Fathiya M Khamis, Samira A Mohamed, Daisy Salifu, Subramanian Sevgan, Komi KM Fiaboe, Saliou Niassy, Joop JA van Loon, Marcel Dicke, et al. (2018). “Threshold temperatures and thermal requirements of black soldier fly Hermetia illucens: Implications for mass production”. In: *PloS one* 13.11, e0206097.

Čičková, Helena, G Larry Newton, R Curt Lacy, and Milan Kozánek (2015). “The use of fly larvae for organic waste treatment”. In: *Waste Management* 35, pp. 68–80.

Comparat, Solène, Antoine Hubert, Fabrice Berro, Jean-gabriel Levon, Frank Launay, Sarton Du, and Jonchay Thibault (2018). “Farm for Rearing Insects”. US Patent App. 15/565,727.

Costa-Neto, EM and FV Dunkel (2016). “Insects as Food: History, Culture, and Modern Use around the World”. In: *Insects as Sustainable Food Ingredients*. Elsevier, pp. 29–60.

Coudron, Carl (2019). Personal communication. Researcher at Inagro, Belgian research institute working on growing efficiency, upscaling and automation of insect production.

de Vries, Marion and Imke JM de Boer (2010). “Comparing environmental impacts for livestock products: A review of life cycle assessments”. In: *Livestock science* 128.1-3, pp. 1–11.

DeFoliart, Gene R (1995). “Edible insects as minilivestock”. In: *Biodiversity & Conservation* 4.3, pp. 306–321.

DeFoliart, Gene R (1999). “Insects as food: why the western attitude is important”. In: *Annual review of entomology* 44.1, pp. 21–50.

Diener, S, C Zurbrügg, and K Tockner (2015). “Bioaccumulation of heavy metals in the black soldier fly, Hermetia illucens and effects on its life cycle”. In: *Journal of Insects as Food and Feed* 1.4, pp. 261–270.

Diener, Stefan, Christian Zurbrügg, Floria Roa Gutiérrez, Dang Hong Nguyen, Antoine Morel, Thammarat Koottatep, and Klement Tockner (2011). “Black soldier fly larvae for organic waste treatment - prospects and constraints”. In: *Proceedings of the WasteSafe* 2011, 2nd.

Diener, Stefan, Christian Zurbrügg, and Klement Tockner (2009). “Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates”. In: *Waste Management & Research* 27.6, pp. 603–610.

Dortmans, Bram (2015). “Valorisation of organic waste : effect of the feeding regime on process parameters in a continuous black soldier fly larvae composting system”. MA thesis. SLU, Dept. of Energy and Technology.

Dortmans, Bram, Siegfried Diener, Verstappen Bart, and Christian Zurbrügg (2017). *Black soldier fly biowaste processing: a Step-by-Step Guide*. Eawag: Swiss Federal Institute of Aquatic Science and Technology.

Dossey, AT, JT Tatum, and WL McGill (2016). “Modern insect-based food industry: current status, insect processing technology, and recommendations moving forward”. In: *Insects as Sustainable Food Ingredients*. Elsevier, pp. 113–152.

Ecoinvent (n.d.). *System Models in ecoinvent 3*. `https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/system-models-in-ecoinvent-3.html`. Accessed May 25th, 2019.

Ekvall, Tomas, Adisa Azapagic, Göran Finnveden, Tomas Rydberg, Bo P Weidema, and Alessandra Zamagni (2016). "Attributional and consequential LCA in the ILCD handbook". In: *The International Journal of Life Cycle Assessment* 21.3, pp. 293–296.

EU (2001). "Regulation (EC) No 999/2001 of the European Parliament and of the Council of 22 May 2001 laying down rules for the prevention, control and eradication of certain transmissible spongiform encephalopathies". In: *Official Journal of the European Union* 147, pp. 1–40.

European Commission (2011). "Commission Regulation (EU) No 142/2011 of 25 February 2011 implementing Regulation (EC) No 1069/2009 of the European Parliament and of the Council laying down health rules as regards animal by-products and derived products not intended for human consumption and implementing Council Directive 97/78/EC as regards certain samples and items exempt from veterinary checks at the border under that Directive". In: *Off J Eur Commun* 50, pp. 1–254.

European Commission (2017a). "Commission regulation (EU) 2017/893 of 24 May 2017 amending annexes I and IV to Regulation (EC) No 999/2001 of the European parliament and of the council and annexes X, XIV and XV to commission regulation (EU) No 142/2011 as regards the provisions on processed animal protein". In: *OJ L*, pp. 92–116.

European Commission (2017b). *Waste - Review of Waste Policy and Legislation*. http://ec.europa.eu/environment/waste/target_review.htm. Accessed May 18th, 2019.

European Food Safety Authority (2015). "Risk profile related to production and consumption of insects as food and feed". In: *EFSA Journal* 13.10, p. 4257.

FAO, ed. (2009). *Global agriculture towards 2050. High Level Expert Forum Issues Paper*. Food and Agriculture Organization of the United Nations. Rome.

FAO (2014a). "Environmental performance of animal feeds supply chains: Guidelines for assessment". In:

FAO (2014b). *The State of World Fisheries and Aquaculture 2014*. Ed. by J. Graziano da Silva. Rome, Italy.

Fischer, Christian Holst, Lars-Henrik Lau Heckmann, Martin Dahl, Palle Hannemann, Jacob Wagner Jensen, Freddy Fogh Sørensen, Peter Foged Larsen, and Kevin Byskov (2018). *WICE - Waste, Insects and Circular Economy*. Tech. rep. Miljø- og Fødevareministeriet.

Fufa, Selamawit Mamo, Reidun Dahl Schlanbusch, Kari Sørnes, Marianne Rose Inman, and Inger Andresen (2016). "A Norwegian ZEB definition guideline". In:

Gahukar, RT (2016). "Edible insects farming: efficiency and impact on family livelihood, food security, and environment compared with livestock and crops". In: *Insects as Sustainable Food Ingredients*. Elsevier, pp. 85–111.

Gerber, Pierre J, Henning Steinfeld, Benjamin Henderson, Anne Mottet, Carolyn Opio, Jeroen Dijkman, Allessandra Falcucci, Giuseppe Tempio, et al. (2013). *Tackling climate change through livestock: a global assessment of emissions and mitigation opportunities.* Food and Agriculture Organization of the United Nations (FAO).

Ghaly, Abdel E and FN Alkoaik (2009). "The yellow mealworm as a novel source of protein." In: *American Journal of Agricultural and Biological Sciences* 4.4, pp. 319–331.

Gligorescu, Anton, Søren Toft, Henrik Hauggaard-Nielsen, Jørgen Aagaard Axelsen, and S Achim Nielsen (2018). "Development, metabolism and nutrient composition of black soldier fly larvae

(Hermetia illucens; Diptera: Stratiomyidae) in relation to temperature and diet". In: *Journal of Insects as Food and Feed* 4.2, pp. 123–133.

Gracey, Erik Olav (2019). Personal communication. BioMar Group Sustainability Specialist.

Halloran, Afton, Nanna Roos, Jørgen Eilenberg, Alessandro Cerutti, and Sander Bruun (2016). "Life cycle assessment of edible insects for food protein: a review". In: *Agronomy for Sustainable Development* 36.4, p. 57.

Hanserud, Ola Stedje, Francesco Cherubini, Anne Falk Øgaard, Daniel B Müller, and Helge Brattebø (2018). "Choice of mineral fertilizer substitution principle strongly influences LCA environmental benefits of nutrient cycling in the agri-food system". In: *Science of The Total Environment* 615, pp. 219–227.

Heckmann, L-H, JL Andersen, J Eilenberg, J Fynbo, R Miklos, Annette Nygaard Jensen, JV Nørgaard, and N Roos (2019). "A case report on invaluable: Insect value chain in a circular bioeconomy". In: *Journal of Insects as Food and Feed* 5.1, pp. 9–13.

Heussler, Carina D, Andreas Walter, Hannes Oberkofler, Heribert Insam, Wolfgang Arthofer, Birgit C Schlick-Steiner, and Florian M Steiner (2018). "Influence of three artificial light sources on oviposition and half-life of the Black Soldier Fly, Hermetia illucens (Diptera: Stratiomyidae): Improving small-scale indoor rearing". In: *PloS one* 13.5, e0197896.

Horne, Martin Johnsen (2019). *Varedeklarasjon fjernvarme BKK*. Tech. rep. Multiconsult.

Huis, Arnold van and Dennis GAB Oonincx (2017). "The environmental sustainability of insects as food and feed. A review". In: *Agronomy for Sustainable Development* 37.5, p. 43.

IEA (2016). "Nordic Energy Technology Perspectives 2016: Cities, Flexibility and Pathways to Carbon-neutrality". In: International Energy Agency.

Igesund, Toralf, Barbro Relling, Ingrid Hitland, and Svein Sande (2014). *Matavfall fra husholdninger - Vurdering av sortering, behandling og gebyrkonsekvens*. Tech. rep. Bergenområdets Interkommunale Renovasjonsselskap (BIR) and COWI.

IPIFF (2018). *The European insect sector today: Challenges, opportunities and regulatory landscape*. `http://ipiff.org/ipiff-vision-paper-on-the-future-of-the-insect-sector-towards-2030/`. International Platform of Insects for Food and Feed. Accessed May 16th 2019.

IPIFF (2019). *Guide on Good Hygiene Practices for European Union (EU) producers of insects as food and feed*. `http://ipiff.org/wp-content/uploads/2019/03/IPIFF_Guide_A4_2019-v5-separate.pdf`. Accessed May 5th 2019.

IPIFF (n.d.). *EU Legislation*. `http://ipiff.org/insects-eu-legislation/`. Accessed May 20th, 2019.

ISO (2006). *Environmental Management: Life Cycle Assessment; Principles and Framework (ISO 14040:2006)*. 2006. International Organization for Standardization.

Jiangyin Brightsail Machinery Co., Ltd. (n.d.). *Large industrial electric oven*. `https://www.alibaba.com/product-detail/large-industrial-electric-oven_60652444931.html?spm=a2700.7724838.2017115.177.3b8f6f913XAVJR`. Accessed April 15th, 2019.

Johansen, Marius, Line Diana Blytt, Svein Otto Sande, and Bjørn Magnus Iversen (2018). *Forprosjekt - Mat til mat*. Tech. rep. Bergenområdets Interkommunale Renovasjonsselskap (BIR) and COWI.

Józefiak, Damian, Agata Józefiak, Bartosz Kierończyk, Mateusz Rawski, Sylwester Światkiewicz, Jakub Długosz, and Ricarda Margarete Engberg (2016). “Insects–a natural nutrient source for poultry–a review”. In: *Annals of animal science* 16.2, pp. 297–313.

Kim, Sun Young, Hong Geun Kim, Kyeong Yong Lee, Hyung Joo Yoon, and Nam Jung Kim (2016). “Effects of Brewers spent grain (BSG) on larval growth of mealworms, Tenebrio molitor (Coleoptera: Tenebrionidae)”. In: *International Journal of Industrial Entomology* 32.1, pp. 41–48.

Kim, Sun Young, Jong Bin Park, Young Bo Lee, Hyung Joo Yoon, Kyeong Yong Lee, and Nam Jung Kim (2015). “Growth characteristics of mealworm Tenebrio molitor”. In: *Journal of Sericultural and Entomological Science* 53.1, pp. 1–5.

Kröncke, Nina, Verena Böschen, Jan Woyzichovski, Sebastian Demtröder, and Rainer Benning (2018). “Comparison of suitable drying processes for mealworms (Tenebrio molitor)”. In: *Innovative Food Science & Emerging Technologies* 50, pp. 20–25.

Laurent, Alexis, Julie Clavreul, Anna Bernstad, Ioannis Bakas, Monia Niero, Emmanuel Gentil, Thomas H Christensen, and Michael Z Hauschild (2014). “Review of LCA studies of solid waste management systems–Part II: Methodological guidance for a better practice”. In: *Waste management* 34.3, pp. 589–606.

Lenaerts, Sanne, Mik Van Der Borght, An Callens, and Leen Van Campenhout (2018). “Suitability of microwave drying for mealworms (Tenebrio molitor) as alternative to freeze drying: Impact on nutritional quality and colour”. In: *Food chemistry* 254, pp. 129–136.

Li, Q, L Zheng, Y Hou, S Yang, and Z Yu (2011). “Insect fat, a promising resource for biodiesel”. In: *J Pet Environ Biotechnol*, S2.

Lindberg, Diana, Kjersti Aaby, Grethe Iren Andersen Borge, John-Erik Haugen, Astrid Nilsson, Rune Rødbotten, and Stefan Sahlstrøm (2016). “Kartlegging av restråstoff fra jordbruket”. In: *Nofima rapportserie*.

Liu, Zhongyi, Maria Minor, Patrick CH Morel, and Adriana J Najar-Rodriguez (2018). “Bioconversion of Three Organic Wastes by Black Soldier Fly (Diptera: Stratiomyidae) Larvae”. In: *Environmental entomology* 47.6, pp. 1609–1617.

Liverød, Tonje (2018). *Rapport om restråstoff som fôrsubstrat til insekter*. Report for internal use by Invertapro.

Lock, ER, T Arsiwalla, and R Waagbø (2016). “Insect larvae meal as an alternative source of nutrients in the diet of A tlantic salmon (S almo salar) postsmolt”. In: *Aquaculture Nutrition* 22.6, pp. 1202–1213.

Maillard, Frédéric, Catherine Macombe, Joel Aubin, Hedi Romdhana, and Samir Mezdour (2018). “Mealworm Larvae Production Systems: Management Scenarios”. In: *Edible Insects in Sustainable Food Systems*. Springer, pp. 277–301.

Makkar, Harinder PS, Gilles Tran, Valérie Heuzé, and Philippe Ankers (2014). “State-of-the-art on use of insects as animal feed”. In: *Animal Feed Science and Technology* 197, pp. 1–33.

Marshall, SA, NE Woodley, and M Hauser (2015). “The historical spread of the Black Soldier Fly, Hermetia illucens (L.)(Diptera, Stratiomyidae, Hermetiinae), and its establishment in Canada”. In: *The Journal of the Entomological Society of Ontario* 146.

Mattilsynet (2016). *Insekter som mat*. `https://www.mattilsynet.no/mat_og_vann/produksjon_av_mat/ny_mat/insekter_som_mat.22375`. Accessed April 11th 2019.

Mattilsynet (2017). *Insekter til bruk i fôr*. https://www.mattilsynet.no/dyr_og_dyrehold/for/insekter_til_bruk_i_for.25298. Accessed April 11th 2019.

Megido, Rudy Caparros, Sandrine Desmedt, Christophe Blecker, François Béra, Éric Haubruge, Taofic Alabi, and Frédéric Francis (2017). "Microbiological load of edible insects found in Belgium". In: *Insects* 8.1, p. 12.

Melis, Riccardo, Angela Braca, Gilberto Mulas, Roberta Sanna, Simona Spada, Giuseppe Serra, Maria Leonarda Fadda, Tonina Roggio, Sergio Uzzau, and Roberto Anedda (2018). "Effect of freezing and drying processes on the molecular traits of edible yellow mealworm". In: *Innovative food science & emerging technologies* 48, pp. 138–149.

Miljødirektoratet (2018). *Forslag til forskrift om utsortering og materialgjenvinning av biologisk avfall og plastavfall*.

Modahl, IS, KA Lyng, A Stensgård, S Saxegård, OJ Hanssen, H Møller, J Morken, T Briseid, and I Sørby (2016). *Biogassproduksjon fra matavfall og møkk fra ku, gris og fjørfe. Status 2016 (fase IV) for miljønytte for den norske biogassmodellen BioValueChain*. Tech. rep. Østfoldforskning AS.

Mondello, Giovanni, Roberta Salomone, Giuseppe Ioppolo, Giuseppe Saija, Sergio Sparacia, and Maria Claudia Lucchetti (2017). "Comparative LCA of Alternative Scenarios for Waste Treatment: The Case of Food Waste Production by the Mass-Retail Sector". In: *Sustainability* 9.5, p. 827.

Morales-Ramos, Juan A, Hans C Kelstrup, M Guadalupe Rojas, and Virginia Emery (2019). "Body Mass Increase Induced by Eight Years of Artificial Selection in the Yellow Mealworm (Coleoptera: Tenebrionidae) and Life History Trade-offs". In: *Journal of Insect Science* 19.2, p. 4.

Morales-Ramos, Juan A and M Guadalupe Rojas (2015). "Effect of larval density on food utilization efficiency of Tenebrio molitor (Coleoptera: Tenebrionidae)". In: *Journal of economic entomology* 108.5, pp. 2259–2267.

Morales-Ramos, Juan A, M Guadalupe Rojas, Sasha Kay, David I Shapiro-Ilan, and W Louis Tedders (2012). "Impact of adult weight, density, and age on reproduction of Tenebrio molitor (Coleoptera: Tenebrionidae)". In: *Journal of entomological science* 47.3, pp. 208–220.

Mutafela, Richard Nasilele (2015). "High Value Organic Waste Treatment Via Black Soldier Fly: Onsite Pilot Study". MA thesis. KTH Royal Institute of Technology.

Muys, B, M Roffeis, B Pastor, P Gobbi, A Martınez-Sánchez, S Rojo, F Zhu, E Mathijs, and WA Achten (2014). "Generic life cycle assessment of proteins from insects. Insects to Feed The World". In: *1st 23 International Conference*, pp. 14–17.

NIFES (2015). *Insekter som laksefôr*. https://nifes.hi.no/en/prosjekt/insects-salmon-feed//. Accessed May 19th, 2019.

NIFES (2017). *From organic waste stream til feed resource: the role of insects in the bio-economy*. https://nifes.hi.no/en/prosjekt/organic-waste-stream-til-feed-resource-role-insects-bio-economy/. Accessed May 19th, 2019.

Norwegian Agriculture Agency (n.d.[a]). *Råvarer brukt i norsk produksjon av kraftfôr til husdyr 2018 (tonn)*. https://www.landbruksdirektoratet.no/no/produksjon-og-marked/korn-og-kraftfor/marked-og-pris/statistikk/_attachment/73754?_ts=1694dda6ff8&download=true. Accessed May 27th, 2019.

Norwegian Agriculture Agency (n.d.[b]). *Total kornproduksjon*. https://www.landbruksdirektoratet.no/no/statistikk/utvikling/produsert-mengde. Accessed June 5th, 2019.

Norwegian Ministry of Agriculture and Food (n.d.). *Soil conservation*. https://www.regjeringen.no/en/topics/food-fisheries-and-agriculture/landbrukseiendommer/innsikt/jordvern/soil-conservation/id2009556/. Accessed May 27th, 2019.

Norwegian Ministry of Climate and Environment (2014). *Nasjonal tverrsektoriell biogasstrategi*.

Norwegian Water Resources and Energy Directorate (2018). *Electricity disclosure 2017*. https://www.nve.no/energy-market-and-regulation/retail-market/electricity-disclosure-2017/. Accessed May 29th, 2019.

Notarnicola, Bruno, Serenella Sala, Assumpció Anton, Sarah J McLaren, Erwan Saouter, and Ulf Sonesson (2017). "The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges". In: *Journal of Cleaner Production* 140, pp. 399–409.

Notarnicola, Bruno, Giuseppe Tassielli, Pietro A Renzulli, and Agata Lo Giudice (2015). "Life Cycle Assessment in the agri-food sector: an overview of its key aspects, international initiatives, certification, labelling schemesand methodological issues". In: *Life Cycle Assessment in the Agri-food Sector*. Springer, pp. 1–56.

Oonincx, Dennis GAB and Imke JM De Boer (2012). "Environmental impact of the production of mealworms as a protein source for humans - a life cycle assessment". In: *PloS one* 7.12, e51145.

Oonincx, Dennis GAB, Sarah Van Broekhoven, Arnold Van Huis, and Joop JA van Loon (2015). "Feed conversion, survival and development, and composition of four insect species on diets composed of food by-products". In: *PLoS One* 10.12, e0144601.

Oonincx, Dennis GAB, Joost Van Itterbeeck, Marcel JW Heetkamp, Henry Van Den Brand, Joop JA Van Loon, and Arnold Van Huis (2010). "An exploration on greenhouse gas and ammonia production by insect species suitable for animal or human consumption". In: *PloS one* 5.12, e14445.

Oonincx, DGAB, N Volk, JJE Diehl, JJA Van Loon, and G Belušič (2016). "Photoreceptor spectral sensitivity of the compound eyes of black soldier fly (Hermetia illucens) informing the design of LED-based illumination to enhance indoor reproduction". In: *Journal of insect physiology* 95, pp. 133–139.

Ortiz, JA Cortes, A Torres Ruiz, JA Morales-Ramos, Menno Thomas, MG Rojas, JK Tomberlin, L Yi, R Han, L Giroud, and RL Jullien (2016). "Insect mass production technologies". In: *Insects as Sustainable Food Ingredients*. Elsevier, pp. 153–201.

Payne, CLR, P Scarborough, M Rayner, and K Nonaka (2016). "Are edible insects more or less 'healthy' than commonly consumed meats? A comparison using two nutrient profiling models developed to combat over-and undernutrition". In: *European journal of clinical nutrition* 70.3, p. 285.

Ponsioen, Tommie (n.d.). *Finding Your Way In Multifunctional Processes And Recycling*. https://www.pre-sustainability.com/news/finding-your-way-in-allocation-methods-multifunctional-processes-recycling. Accessed May 25th, 2019.

Premalatha, M, Tasneem Abbasi, Tabassum Abbasi, and SA Abbasi (2011). "Energy-efficient food production to reduce global warming and ecodegradation: The use of edible insects". In: *Renewable and sustainable energy reviews* 15.9, pp. 4357–4360.

Rasmussen, Lone Lindgaard, Amparo Gómez Cortina, Marie Søndergaard, Niels Finn Johansen, Eleonora Miquel Becker, and Lars-Henrik Lau Heckmann (2016). *INBIOM Bobleprojekt: Udnyttelse af restbiomasser til insektproduktion af proteinfoder med melorme*. Tech. rep. Danish Technological Institute.

Ribeiro, Nuno, Manuela Abelho, and Rui Costa (2018). "A Review of the Scientific Literature for Optimal Conditions for Mass Rearing Tenebrio molitor (Coleoptera: Tenebrionidae)". In: *Journal of Entomological Science* 53.4, pp. 434–454.

Rijlaarsdam, Wim (2019). Personal communication. RFA Rijlaarsdam Factory Automation B.V.

Ringheim, Alexander Solstad (2019). Personal communication. CEO of Invertapro, Norwegian insect production start-up located in Voss.

Roffeis, Martin, Bart Muys, Joana Almeida, Erik Mathijs, WMJ Achten, B Pastor, Yelitza Velásquez, Ana Isabel Martinez-Sanchez, and Santos Rojo (2015). "Pig manure treatment with housefly (Musca domestica) rearing–an environmental life cycle assessment". In: *Journal of Insects as Food and Feed* 1.3, pp. 195–214.

Roffeis, Martin, Joana Almeida, Maureen Elizabeth Wakefield, Tatiana Raquel Alves Valada, Emilie Devic, N'Golopé Koné, Marc Kenis, Saidou Nacambo, Elaine Charlotte Fitches, Gabriel KD Koko, et al. (2017). "Life Cycle Inventory analysis of prospective insect based feed production in West Africa". In: *Sustainability* 9.10, p. 1697.

Rumpold, Birgit A and Oliver K Schlüter (2013a). "Nutritional composition and safety aspects of edible insects". In: *Molecular nutrition & food research* 57.5, pp. 802–823.

Rumpold, Birgit A and Oliver K Schlüter (2013b). "Potential and challenges of insects as an innovative source for food and feed production". In: *Innovative Food Science & Emerging Technologies* 17, pp. 1–11.

Rustad, Ida Hexeberg (2016). "Life cycle assessment of fish feed produced from the black soldier fly (Hermetia illucens)". MA thesis. NTNU.

Salomone, R, G Saija, G Mondello, A Giannetto, S Fasulo, and D Savastano (2016). "Environmental impact of food waste bioconversion by insects: application of life cycle assessment to process using Hermetia illucens". In: *Journal of Cleaner Production* 140, pp. 890–905.

Salou, Thibault, Sandrine Espagnol, Armelle Gac, Paul Ponchant, Aurélien Tocqueville, Vincent Colomb, Hayo MG van der Werf, et al. (2014). "Life Cycle Assessment of French livestock products: Results of the AGRIBALYSE® program". In: *Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector*, pp. 1154–1162.

Sánchez-Muros, Marıa-José, Fernando G Barroso, and Francisco Manzano-Agugliaro (2014). "Insect meal as renewable source of food for animal feeding: a review". In: *Journal of Cleaner Production* 65, pp. 16–27.

Saxegård, Simon Alexander (2015). "Life cycle assessment of biogas production from organic waste sources in a Norwegian context". MA thesis. NTNU.

Schillewaert, Sharon, Filiep Vincent, and Jonas Claeys (2016). *Proof of concept: Automatische voederlijn in de meelworm kweek*. Tech. rep. Vives, Sirris, and Inagro.

Schmidt, Jannick H (2015). “Life cycle assessment of five vegetable oils”. In: *Journal of Cleaner Production* 87, pp. 130–138.

Siemianowska, Ewa, Agnieszka Kosewska, Marek Aljewicz, Krystyna A Skibniewska, Lucyna Polak-Juszczak, Adrian Jarocki, and Marta Jedras (2013). “Larvae of mealworm (Tenebrio molitor L.) as European novel food”. In: *Agricultural Sciences* 4.06, p. 287.

Silva, Catarina Basto, Luısa MP Valente, Elisabete Matos, Miguel Brandão, and Belmira Neto (2018). “Life cycle assessment of aquafeed ingredients”. In: *The International Journal of Life Cycle Assessment* 23.5, pp. 995–1017.

Skretting (2018). *Insect meal now in commercial Skretting feed*. https://www.skretting.com/en/media/news/insect-meal-now-in-commercial-skretting-feed/1588652. Accessed May 19th, 2019.

Smetana, Sergiy, Alexander Mathys, Achim Knoch, and Volker Heinz (2015). “Meat alternatives: life cycle assessment of most known meat substitutes”. In: *The International Journal of Life Cycle Assessment* 20.9, pp. 1254–1267.

Smetana, Sergiy, Megala Palanisamy, Alexander Mathys, and Volker Heinz (2016). “Sustainability of insect use for feed and food: life cycle assessment perspective”. In: *Journal of cleaner production* 137, pp. 741–751.

Smetana, Sergiy, Eric Schmitt, and Alexander Mathys (2019). “Sustainable use of Hermetia illucens insect biomass for feed and food: Attributional and consequential life cycle assessment”. In: *Resources, Conservation and Recycling* 144, pp. 285–296.

Sørensen, Mette, Gerd Marit Berge, Magny S Thomassen, Bente Ruyter, Bjarne Hatlen, Trine Ytrestøyl, Turid Synnøve Aas, and Torbjørn Einar Åsgård (2011). “Today’s and tomorrow’s feed ingredients in Norwegian aquaculture”. In: *Nofima rapportserie*.

Sørgard, Kaja Daviknes (2018). “Environmental analysis of alternative food waste solutions in the urban waste system of BIR”. MA thesis. NTNU.

Statistics Norway (2018). *Avfall frå hushalda*. https://www.ssb.no/avfkomm. Accessed May 29th, 2019.

Temple, Wayne D, Reed Radley, Jay Baker-French, and Foster Richardson (2013). “Use of Enterra Natural Fertilizer (Black Soldier Fly Larvae Digestate) As a Soil Amendment”. In:

Thévenot, Alexandre, Julio L Rivera, Aurélie Wilfart, Frédéric Maillard, Melynda Hassouna, Tristan Senga-Kiesse, Samuel Le Féon, and Joël Aubin (2018). “Mealworm meal for animal feed: Environmental assessment and sensitivity analysis to guide future prospects”. In: *Journal of Cleaner Production* 170, pp. 1260–1267.

Tomberlin, Jeffery K, D Craig Sheppard, and John A Joyce (2002). “Selected life-history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets”. In: *Annals of the Entomological Society of America* 95.3, pp. 379–386.

UN (2017). *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248*. Tech. rep.

Van Huis, Arnold, Joost Van Itterbeeck, Harmke Klunder, Esther Mertens, Afton Halloran, Giulia Muir, and Paul Vantomme (2013). *Edible insects: future prospects for food and feed security*. Food and Agriculture Organization of the United Nations.

van Zanten, Hannah HE, Herman Mollenhorst, Dennis GAB Oonincx, Paul Bikker, Bastiaan G Meerburg, and Imke JM de Boer (2015). “From environmental nuisance to environmental opportunity: housefly larvae convert waste to livestock feed". In: *Journal of Cleaner Production* 102, pp. 362–369.

Veldkamp, T, G Van Duinkerken, A Van Huis, CMM Lakemond, E Ottevanger, G Bosch, and T Van Boekel (2012). *Insects as a Sustainable Feed Ingredient in Pig and Poultry Diets: a Feasibility Study*. Tech. rep. Wageningen UR Livestock Research.

Veldkamp, Teun and Guido Bosch (2015). "Insects: a protein-rich feed ingredient in pig and poultry diets". In: *Animal Frontiers* 5.2, pp. 45–50.

Vellinga, Th V, H Blonk, M Marinussen, WJ Van Zeist, and DAJ Starmans (2013). *Methodology used in feedprint: a tool quantifying greenhouse gas emissions of feed production and utilization*. Tech. rep. Wageningen UR Livestock Research.

Wang, Hui, Kashif ur Rehman, Xiu Liu, Qinqin Yang, Longyu Zheng, Wu Li, Minmin Cai, Qing Li, Jibin Zhang, and Ziniu Yu (2017). "Insect biorefinery: a green approach for conversion of crop residues into biodiesel and protein". In: *Biotechnology for biofuels* 10.1, p. 304.

Wynants, Enya, Sam Crauwels, Bart Lievens, Stijn Luca, Johan Claes, An Borremans, Lise Bruyninckx, and Leen Van Campenhout (2017). "Effect of post-harvest starvation and rinsing on the microbial numbers and the bacterial community composition of mealworm larvae (Tenebrio molitor)". In: *Innovative food science & emerging technologies* 42, pp. 8–15.

Yi, C., He Qiuju, Wang Lin, and Rongping Kuang (2010). "The utilization of insect-resources in Chinese rural area". In: *Journal of Agricultural Science* 2.3, p. 146.

Zahn, Nils Holger (2017). "The effects of insect frass created by Hermetia illucens on spring onion growth and soil fertility". Bachelor's Thesis.

Zhang, Jibin, Ling Huang, Jin He, Jeffery K Tomberlin, Jianhong Li, Chaoliang Lei, Ming Sun, Ziduo Liu, and Ziniu Yu (2010). "An artificial light source influences mating and oviposition of black soldier flies, Hermetia illucens". In: *Journal of insect science* 10.1.

Zong, Liang, Yi Guo, Wencai Du, and Yong Bai (2015). "Design of a live animal vibration automatic control screening machine based on meta-component and semantic similarity principle". In: *Journal of Vibroengineering* 17.8, pp. 4533–4544.

Appendix A

Inventory calculations

A.1 Black soldier fly production facility

The report by Smetana et al. (2019) was used as inventory for the foreground processes in the black soldier fly production facility. This report contained a relatively detailed inventory of consumption of different resources by different processing stages when producing the black soldier fly, as reproduced in the first five columns of table 3.2. To model the entire production of black soldier fly based on a total incoming amount of feeding substrate of 24 687.5 tons per year, the input of different resources had to be calculated for this specific amount. Conversion ratios from feed to larvae and from live larvae to different products as given by Smetana et al. were used to calculate these numbers. The ratios are as follows: To produce 1 kg of insect meal, 6.26 kg of BSF larvae is needed. To feed these larva until they are ready to be harvested, 32.24 kg of feed is required. For each kg of meal produced, 3.82 kg of ready-for use fertilizer is also produced, in addition to 1.44 kg of insect puree and 0.34 kg insect lipids (oil).

To find total meal production per year, the total amount of incoming feeding substrate was divided by the total feed input needed per 6.26 kg BSF larvae, which would facilitate the production of 1 kg meal:

$$\text{total amount of BSF meal produced} = \frac{246\ 875\ 000\ \frac{\text{kg feeding substrate}}{\text{year}}}{32.24\ \frac{\text{kg feeding substrate}}{\text{kg meal}}} = 765\ 741 \frac{\text{kg BSF meal}}{\text{year}}$$

This amount was further used to calculate the output of the other products, as the ratios were given per kg meal produced:

$$\begin{aligned}\text{total amount of fresh BSF fertilizer produced} &= 3.82\ \frac{\text{kg fertilizer}}{\text{kg meal}} * 765\ 741 \frac{\text{kg meal}}{\text{year}} \\ &= 2\ 925\ 132\ \frac{\text{kg BSF fertilizer}}{\text{year}}\end{aligned}$$

$$\begin{aligned}\text{total amount of BSF larvae produced} &= 6.25\ \frac{\text{kg fresh larvae}}{\text{kg meal}} * 765\ 741 \frac{\text{kg meal}}{\text{year}}\\ &= 4\ 793\ 541\ \frac{\text{kg fresh larvae}}{\text{year}}\end{aligned}$$

$$\begin{aligned}\text{total amount of BSF puree produced} &= 1.44\ \frac{\text{kg puree}}{\text{kg meal}} * 765\ 741 \frac{\text{kg meal}}{\text{year}}\\ &= 1\ 102\ 667\ \frac{\text{kg BSF puree}}{\text{year}}\end{aligned}$$

$$\begin{aligned}\text{total amount of BSF oil produced} &= 0.34\ \frac{\text{kg oil}}{\text{kg meal}} * 765\ 741 \frac{\text{kg meal}}{\text{year}}\\ &= 260\ 352\ \frac{\text{kg BSF oil}}{\text{year}}\end{aligned}$$

For the processes connected to the insect nursery, it was also necessary to calculate the quantity of eggs necessary to produce 1 kg of fresh larvae. Agriprotein, a renowned insect production company in South Africa reports that 1 g of BSF larvae turns into 5.7 kg live larvae (Agriprotein, n.d.). This ratio was used to find the total production of BSF eggs necessary to produce the 2 925 132 kg of fresh larvae per year:

$$\begin{aligned}\text{total amount of BSF eggs produced} &= \frac{0.001\text{ kg eggs}}{5.7\text{ kg fresh larvae}} * 4\ 793\ 541\ \frac{\text{kg fresh larvae}}{\text{year}}\\ &= 841\ \frac{\text{kg BSF eggs}}{\text{year}}\end{aligned}$$

The total sum of products from the BSF production was found by adding the amounts of the different end products:

$$\begin{aligned}\text{total amount of BSF products produced} &= 765\ 741 \frac{\text{kg BSF meal}}{\text{year}} + 2\ 925\ 132\ \frac{\text{kg BSF fertilizer}}{\text{year}}\\ &+ 1\ 102\ 667\ \frac{\text{kg BSF puree}}{\text{year}} + 260\ 352\ \frac{\text{kg BSF oil}}{\text{year}}\\ &= 5\ 053\ 893\ \frac{\text{kg BSF end products}}{\text{year}}\end{aligned}$$

These amounts were used to find the total amount needed of different resources for different processes in the BSF production factory by multiplication by the respective product, i.e. per kg meal, oil, fertilizer, egg or product.

A.2 Yellow mealworm production facility

Various data sources was used to compile the inventory for the production of yellow mealworms. Most processes in the inventory is given per kg of fresh mealworm larvae produced, which is modelled to be 1000 tons per year. However, some calculations have been made to convert primary data into applicable data. These calculations are presented here.

A.2.1 Use of robots for feeding and transportation of crates

Data on the operational conditions of the cell-based feeding robots used for feeding and transport in this study is based on primary data obtained directly from the designers of this system, namely Inagro, Sirris and Vives in Belgium. The life cycle is assumed to be 9 weeks from egg to harvest-ready larvae. There has to be continuous production, as mealworms are living animals which require continuous attention. The total production of fresh mealworm larvae is dimensioned to be 1000 tons per year. The cell-based system is designed so that each cell contains 380 crates, distributed in stacks of 10 crates per stack. This gives a total of 38 stacks in each cell. Each crate is reported to produce 2 kg fresh mealworms at the end of each cycle time. Using this information, the total amount of cycles each year can be calculated, which can be further used to calculate the total number of cells required to produce 1000 tons of fresh larvae per year.

$$\text{cycles per year} = \frac{52\,\frac{\text{weeks}}{\text{year}}}{9\,\frac{\text{weeks}}{\text{cycle}}} = 5.78\,\frac{\text{cycles}}{\text{year}}$$

The number of cycles per year can be used to find total production per cell and year:

$$\text{production per cell} = 5.78\,\frac{\text{cycles}}{\text{year}} * 0.002\,\frac{\text{tons fresh larvae}}{\text{crate}} * 380\,\frac{\text{crates}}{\text{cell}} = 4.391\,\frac{\text{tons fresh larvae}}{\text{cell \& year}}$$

This can further be used to find the total number of cells required to produce the 1000 tons of fresh larvae:

$$\text{number of cells} = \frac{1000\,\frac{\text{tons fresh larvae}}{\text{year}}}{4.391\,\frac{\text{tons fresh larvae}}{\text{cell \& year}}} = 227.73\text{ cells}$$

However, this number of cells needs to be a whole number as this corresponds to the physical construction of cells, and the total number of cells is therefore rounded up to 228 cells. This can further be used to calculate the total number of crates used in the production of yellow mealworms:

$$\text{total number of crates for production} = 380\,\frac{\text{crates}}{\text{cell}} * 228\text{ cells} = 86\,640\text{ crates}$$

The number of feeding robots needed to service these cells can be calculated based on the operational characteristics of the robot. Inagro, Sirris and Vives reports that one robot uses 1.5

kW of electricity in an operational period of 8 hours per day, servicing 4000 crates in this time. Assuming that the robots operate for 24 hours a day, the total number of crates serviced by one robot is:

$$\text{crates serviced by one robot} = 4000\ \frac{\text{crates}}{\text{day \& robot}} * \frac{24\ \frac{\text{hours}}{\text{day}}}{8\ \frac{\text{hours}}{\text{day}}} = 12\ 000\ \frac{\text{crates}}{\text{day \& robot}}$$

This can be used to find the total number of robot necessary to feed all crates in all cells once each day:

$$\text{robots needed for feeding all crates} = \frac{86\ 640\ \frac{\text{crates}}{day}}{12\ 000\ \frac{\text{crates}}{\text{day \& robot}}} = 7.220\ \text{robots}$$

As with the total number of cells, the total number of robots must be a whole number. This number is therefore rounded up to 8, as the number of robots must at least be able to service all crates once each day. Each of these robots uses the reported 1.5 kW and operates for 24 hours each day, 365 days each year. The electricity consumption of one robot can thereby be found:

$$\text{electricity consumption by } \textit{one} \text{ robot} = 1.5\ \frac{\text{kW}}{\text{robot}} * 24\ \frac{\text{h}}{\text{day}} * 365\ \frac{\text{days}}{\text{year}} = 13\ 140\ \frac{\text{kWh}}{\text{robot \& year}}$$

Total power consumption by all feeding robots is thus:

$$\text{electricity consumption by } \textit{all} \text{ feeding robots} = 13\ 140\ \frac{\text{kWh}}{\text{robot \& year}} * 8\ \text{robots} = 105\ 120\ \frac{\text{kWh}}{\text{year}}$$

Dividing this number by the total yearly production of fresh mealworms, the electricity consumption of the feeding process per kg of larvae produced is obtained:

$$\begin{aligned} \text{electricity consumption by all feeding robots per output} &= \frac{105\ 120\ \frac{\text{kWh}}{\text{year}}}{1\ 000\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}} \\ &= 0.1051\ \frac{\text{kWh}}{\text{kg fresh larvae}} \end{aligned} \tag{A.1}$$

As stated in section 3.2.1, a robot similar to that used for feeding is assumed to be operating on the backside of the cells, to transport crates back and forth to other processing activities such as screening, harvesting and further processing. These activities are not as frequent as the feeding process, and one robot is assumed to be able to service all cells. This is confirmed by calculating the total number of days it takes one robot to serve all crates in the production:

$$\text{time for } \textit{one} \text{ robot to service all crates once} = \frac{86\ 640 \text{ crates}}{12\ 000\ \frac{\text{crates}}{\text{day}}} = 7.22 \text{ days}$$

Each crate must only be screened approximately every 15th day according to Zong et al. (2015), so only using one robot for transportation is considered to be an acceptable choice. However, if the vertical farming concept is implemented, this is no longer a valid choice. Modifying the robot to move both sideways and up and down to service cells on multiple floors is considered to be no simple feat as it requires more complex infrastructure. Thus, if cells are stacked to use floor area more efficiently, an extra robot must be included per additional floor.

Based on the design by Inagro, Sirris and Vives, each production cell is 3.1 meters wide and 4.8 meters long, making the area occupied by each cell 14.88 m^2. Each cell is 3 meters high, which means that stacking two cells to a total of 6 meters is a reasonable height to expect from an industrial-sized factory. Stacking of two cells is therefore assumed in this study, which by the argument above requires two robots for transportation of crates. Each robot uses the same amount of electricity as the robots used for feeding, i.e. 13 140 kWh per year. The total electricity consumption by the two robots needed for transportation of crates is thus:

$$\text{electricity consumption by two transportation robots} = 13\ 140\ \frac{\text{kWh}}{\text{robot \& year}} * 2 \text{ robots} = 26\ 280\ \frac{\text{kWh}}{\text{year}}$$

Dividing this number by the total yearly production of fresh mealworms, the electricity consumption of the process of transporting crates within the factory per kg of larvae produced is obtained:

$$\begin{aligned}\text{electricity consumption by all transportation robots per output} &= \frac{26\ 280\ \frac{\text{kWh}}{\text{year}}}{1\ 000\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}} \\ &= 0.0263\ \frac{\text{kWh}}{\text{kg fresh larvae}}\end{aligned} \tag{A.2}$$

Equations A.1 and A.2 thus give the final values presented in table 3.2.1 for the operation of automated feeding and crate transportation in the production facility for yellow mealworms based on primary data obtained from Vives, Sirris and Inagro (Schillewaert et al., 2016).

A.2.2 Use of robot for reproduction activities

As the life stages in the reproduction stage must be handled more frequently than the larvae kept in the cells, another automated system, different from the system developed by Vives, Sirris and Inagro, was used to model this processing stage. In addition to the primary data on the feeding and transport of crates, primary data was therefore also obtained for another type of robot developed for use in automated yellow mealworm production. RFA Rijlaarsdam Factory Automation B.V. in Belgium has made a robot for for feeding and de-palletising crates, as described in section 2.5.5.

For the reproduction activities, approximately two crates are needed per one crate of larvae. This includes crates of mating adults, as well as crates with larvae which are taken from production for pupation to maintain the colony. The larvae becomes pupae, and the pupae turns into beetles, which mates and lays eggs, coming full circle. This ratio is used to calculate the number of crates needed for these life stages of the yellow mealworm production:

$$\text{total number of crates for reproduction} = \frac{86\,640 \text{ crates}}{2} = 43\,320 \text{ crates}$$

As no detailed information is available for the specific automated operations necessary to handle all activities related to reproduction, the robot developed by RFA Rijlaarsdam Factory Automation B.V is assumed to be able to carry out the necessary operations. Each robot is reported to have a maximum power rating of 10 kVA, which corresponds to 8 kW. The total electricity use of one robot is thus:

$$\text{electricity consumption by } \textit{one} \text{ robot} = 8\,\frac{\text{kW}}{\text{robot}} * 24\,\frac{\text{h}}{\text{day}} * 365\,\frac{\text{days}}{\text{year}} = 70\,080\,\frac{\text{kWh}}{\text{robot \& year}}$$

This system was developed to be able to de-palletise and palletise 2000 crates in 8 hours, which means that it has a capacity of palletising and de-palletising 250 crates per hour. The de-palletising concept allows for more flexible movement, which enables easier adaption to more frequent and specialized handling compared to the robot designed by Inagro, Sirris and Vives. All crates associated with reproduction is assumed to need handling once per day, either for feeding (yellow mealworm adults need food, in contrast to the adult BSF) or screening. Assuming that all robots operate 24 hours per day, the total number of robots needed to service all reproduction crates can be found using the capacity of one robot:

$$\text{total number of robots for reproduction} = \frac{43\,320 \text{ crates}}{250\,\frac{\text{crates}}{\text{robot \& hour}}}/24 \text{ hours} = 7.220 \text{ robots}$$

However, the total number of robots must be a whole number, and is therefore rounded up to 8. It should be noted that this concept is not cell-based, and it assumed that the crates are kept in stacks, with the robots spaced evenly between so that all crates are within range using a rail system on the ground. The total electricity use by all robots is thus:

$$\text{electricity consumption by } \textit{all} \text{ reproduction robots} = 70\,080\,\frac{\text{kWh}}{\text{robot \& year}} * 8 \text{ robots} = 560\,640\,\frac{\text{kWh}}{\text{year}}$$

Dividing this number by the total yearly production of fresh mealworms, the electricity consumption of the reproduction activities necessary to produce the desired output per kg of larvae produced is obtained:

$$\begin{aligned}\text{electricity consumption by all handling robots for reproduction} &= \frac{560\ 640\ \frac{\text{kWh}}{\text{year}}}{1\ 000\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}} \\ &= 0.5606\ \frac{\text{kWh}}{\text{kg fresh larvae}}\end{aligned} \tag{A.3}$$

Equation A.3 thus represents the final value presented in table 3.2.1 for the feeding and handling of crates in the reproduction part of the production facility for yellow mealworms based on primary data obtained from RFA Rijlaarsdam Factory Automation B.V.

Screening

As mentioned in section 2.5.5, the crates containing all life stages of mealworms must be screened regularly to sieve out the excreta. Screening is based on simple technology, and neither Inagro, Sirris and Vives or RFA Rijlaarsdam Factory Automation B.V. have focused on automating this process. No primary data on large-scale screening processes is thus available at this time, and data for this process for use in the reproduction step and insect production step was therefore obtained from Maillard et al. (2018) as this study both reports on the capacity and power consumption of this specific process.

For the screening activity in the insect production stage, the value obtained for electricity use for screening per kg fresh larvae was used. Assuming that each crate of larvae must be screened every 15$^{\text{th}}$ day, as suggested by Zong et al. (2015), each crate must be screened twice between egg stage and harvest-ready stage, i.e. week 3 and 6, as the crate is also screened as a part of the harvesting process, i.e. in week 9. The value obtained for screening based on the study by Maillard et al. (2018), which is equal in both scenario 1 and 3, is therefore used to find electricity consumption of the screening in the bioconversion step:

$$\begin{aligned}\text{electricity consumption screening of larvae} &= 0.0036\ \frac{\text{kWh}}{\text{kg fresh larvae \& year}} * 2 \\ &= 0.0072\ \frac{\text{kWh}}{\text{kg fresh larvae \& year}}\end{aligned} \tag{A.4}$$

Equation A.4 thus represents the final value presented in table 3.2.1 for the screening of larvae during the bioconversion step in the production facility for yellow mealworms based on primary data obtained from RFA Rijlaarsdam Factory Automation B.V.

For the reproduction stage, no exact sieving frequency is known. It is therefore assumed that the electricity consumption for this screening is half that of the insect production stage, i.e. the same as used in the post-processing steps, as the reproduction stage only has half the number of crates as the bioconversion step. This assumption adds uncertainty to the results, but the electricity input needed for screening is very low compared to the electricity input needed for many of the other processes. This uncertainty will therefore most likely not affect the results drastically, and is deemed to be acceptable in this study.

$$\text{electricity consumption screening of reproduction stages} = 0.0036 \, \frac{\text{kWh}}{\text{kg fresh larvae \& year}} \quad \text{(A.5)}$$

Equation A.5 thus represents the final value presented in table 3.2.1 for the screening of the life stages in the reproduction step in the production facility for yellow mealworms based on primary data obtained from RFA Rijlaarsdam Factory Automation B.V.

A.2.3 Handling crates in post-processing

When the larvae are harvest-ready, they are transported to post-processing for slaughter and further processing into end-products by the modified feeding robot as described above. When the crates arrive at the designated area for post-processing, they must be taken off the transportation robot and further entered into the post-processing sequence. In this study, this operation is assumed to be performed by a robot of the kind developed by RFA Rijlaarsdam Factory Automation B.V., i.e. similar to the robots used for the reproduction step. This operation would require some modifications of the original set-up of the robot, which is assumed to be feasible within the scope of this study. It is assumed that all crates are transported to one point, where this robot will pick up each crate, and empty it into the screening machine which is the first step of the processing, both when the larvae are going to be processed into whole, dried larvae and when they are to be processed into meal and oil. It is assumed that one robot is able to handle all crates, as one robot has the capacity to handle 250 crates/h, which means that one robot can handle all crates in:

$$\text{time for robot to handle all crates once} = \frac{86\,640 \, \frac{\text{crates}}{\text{cycle}}}{250 \, \frac{\text{crates}}{\text{robot \& hour}}} = 347 \, \frac{\text{crates}}{\text{cycle \& robot}}$$

However, each crate must be handled more than once per year, as each crate goes through several cycles of mealworms each year. The robot is assumed to operate the exact number of hours necessary to handle all crates once per cycle. The total number of operational hours is thus:

$$\text{total operational hours for crate handling robot} = 347 \, \frac{\text{hours}}{\text{cycle}} * 5.78 \, \frac{\text{cycles}}{\text{year}} = 2002 \, \frac{\text{hours}}{\text{year}}$$

The electricity consumption of this robot can thus be found based on the operational hours and the power rating of the robot (i.e. 8 kW, as previously mentioned):

$$\text{electricity consumption by crate handling robot} = 8 \text{ kW} * 2002 \, \frac{\text{hours}}{\text{year}} = 16\,019 \, \frac{\text{kWh}}{\text{year}}$$

Dividing this number by the total yearly production of fresh mealworms, the electricity consumption of the crate handling robot per kg of larvae produced is obtained:

$$\begin{aligned}\text{electricity consumption crate handling robot per output} &= \frac{16\,019\ \frac{\text{kWh}}{\text{year}}}{1\,000\,000\ \frac{\text{kg fresh larvae}}{\text{year}}} \\ &= 0.0160\ \frac{\text{kWh}}{\text{kg fresh larvae}}\end{aligned} \tag{A.6}$$

Equation A.6 thus represents the final value presented in table 3.2.1 for the handling of crates for further processing in the production facility for yellow mealworms based on primary data obtained from RFA Rijlaarsdam Factory Automation B.V.

A.2.4 Post-processing into whole, dried larvae

The processing of whole, fresh yellow mealworm larvae into whole, dried larvae for human consumption is modelled based on scenario 1 presented by Maillard et al. (2018). The data used to calculate the energy demand for the different processes included in the post-processing step for producing whole, dried larvae can be found in table A.1.

Table A.1: Material flows and energy data for scenario 1 from Maillard et al. (2018)

Process	**Material flow rate [kg/h]**	**Power [kW]**
Screening	3943	14
Heat treatment	3943	248
Drying	3990	2693

The necessary operational time for each process can be found by dividing the total processing amount, namely 500 000 kg of fresh yellow mealworm larvae per year, with the material flow rates of each process. Multiplying the operational time of each process with the given power rating of each process, the total energy consumption of each process per year can be found. Energy consumption per kg fresh larva can be found by dividing the energy consumption of each process by the total processing amount of 500 000 kg fresh yellow mealworm larvae per year. The calculated values for each process can be found in table A.2.

A.2.5 Post-processing into inset meal

The same calculation steps used for processing fresh mealworms larvae into whole, dried larvae was used for the processing of fresh larvae into meal and oil. Scenario 3 presented by Maillard et

Table A.2: Calculated inventory data for whole, dried larvae based on Maillard et al. (2018)

Process	**Operational time [h]**	**[kWh/year]**	**[kWh/kg fresh larvae & year]**
Screening	127	1775	0.0036
Heat treatment	127	31448	0.0629
Drying	125	337469	0.6749

al. (2018) was used to obtain material flow rates and energy rating, and the same calculation steps as described above was used to obtain the operational time and final energy consumption. The data used and the calculated values for each process can be found in table A.3.

Table A.3: Material flows and energy data for scenario 3 from Maillard et al. (2018) and calculated inventory data for processing off fresh larvae into meal and oil

Process	**Material flow rate [kg/h]**	**Power[kW]**	**Operational time [h]**	**[kWh/year]**	**[kWh/kg fresh larvae & year]**
Screening	4442	16	113	1801	0.0036
Heat treatment	4442	280	113	31517	0.0630
Pressing	4496	281	111	31250	0.0625
Centrifugation	1680	1	298	298	0.0006
Drying	3238	1824	154	281655	0.5633
Evaporation	1348	579	371	214763	0.4295

A.2.6 Post-processing of insect excreta

The insect excreta from must be heat treated before it is used as fertilizer. Lacking specific data, and online research for a suitable industrial scale oven was preformed. An industrial oven from Jiangyin Brightsail Machinery Co., Ltd. was used to model the heat-treatment of frass in this study. This oven has a power rating of 1.5 kW, and a capacity of 480 kg per batch (Jiangyin Brightsail Machinery Co., Ltd., n.d.). Using the procedure described by Invertapro, i.e. heating at 70 °C for 1 hour, the total electricity consumption is assumed to be:

$$\text{electricity consumption for heat treatment of frass} = \frac{1.5\ \text{kW} * 1\ \frac{\text{hour}}{\text{batch}}}{480\ \frac{\text{kg frass}}{\text{batch}}} = 0.0038\ \frac{\text{kWh}}{\text{kg frass}}$$

A.2.7 Final end products

The final quantity of end products are also calculated based on data from Maillard et al. (2018), which gives the material flow rates into the post-processing, in addition to the material flow rate of end products. This can be used to calculate the total amount of each end product.

For the whole, dried larvae, scenario 1 from Maillard et al. (2018) was used to model the processing, in which it was reported that 3943 kg of fresh, live mealworms were processed into 1577 kg whole, dried larvae (using meal as a proxy for whole dried larvae). This gives a total production of whole dried larvae:

$$\text{total amount of whole, dried yellow mealworm larvae produced} = \frac{500\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}}{\frac{3943\ \text{kg fresh larvae}}{1577\ \text{kg whole, dried larvae}}}$$
$$= 199\ 975\ \frac{\text{kg whole, dried larvae}}{\text{year}}$$

For the meal, scenario 3 from Maillard et al. (2018) was used to model the processing, in which it was reported that 4442 kg of fresh, live mealworms were processed into 1577 kg meal (using meal as a proxy for whole dried larvae). This gives a total production of meal:

$$\begin{aligned}\text{total amount of yellow mealworm meal} &= \frac{500\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}}{\frac{4442\ \text{kg fresh larvae}}{1577\ \text{kg meal}}}\\ &= 177\ 510\ \frac{\text{kg meal}}{\text{year}}\end{aligned}$$

Similarly, scenario 3 was used to model the processing into oil (which is a by-product of the meal production). The mass flow ending up as oil is according to the flows in figure 3.5 the mass flow going into centrifugation minus, which is reported to be 1680 kg, minus the mass flow going into the decanting processing step, which is reported to be 1479 kg. This gives a total mass flow of yellow mealworm oil of 201 kg. This means that of the reported input of 4441 kg fresh live mealworms for meal production, a total of 201 oil is made. The total amount of oil produced can thus be calculated as:

$$\text{total amount of yellow mealworm oil} = \frac{500\ 000\ \frac{\text{kg fresh larvae}}{\text{year}}}{\frac{4442\ \text{kg fresh larvae}}{201\ \text{kg oil}}} = 22\ 625\ \frac{\text{kg oil}}{\text{year}}$$

The total amount of insect fertilizer which is produced is based on a ratio provided by Invertapro of 3.316 kg frass per kg fresh mealworm. This gives the total amount of insect fertilizer produced from the yellow mealworm production:

$$\begin{aligned}\text{total amount of yellow mealworm fertilizer} &= 1\ 000\ 000\ \frac{\text{kg fresh larvae}}{\text{year}} * 3.316 \frac{\text{kg fertilizer}}{\text{kg fresh larvae}}\\ &= 3\ 316\ 000\ \frac{\text{kg fertilizer}}{\text{year}}\end{aligned}$$

The total amount of products produced from the yellow mealworm production is thus:

$$\begin{aligned}\text{total amount of yellow mealworm products} &= 199\ 975\ \frac{\text{kg whole, dried larvae}}{\text{year}} + 177\ 510\ \frac{\text{kg meal}}{\text{year}}\\ &+ 22\ 625\ \frac{\text{kg oil}}{\text{year}} + 3\ 316\ 000\ \frac{\text{kg fertilizer}}{\text{year}}\\ &= 3\ 716\ 110\ \frac{\text{kg products}}{\text{year}}\end{aligned}$$

A.3 Direct impacts

A.3.1 GHG emissions

Data from Oonincx et al. (2010) is used to calculate the direct emission of GHGs from the yellow mealworms from their respiratory activities. In the study by Oonincx et al., the GHG production by yellow mealworm was found to be limited to N_2O, as no methane was detected. The N_2O found for the yellow mealworm was 69 mg per kg biomass and day. The total production of fresh, live yellow mealworm larvae is modelled to be 1 000 000 kg in this study. Multiplying this with the total number of days in a year, i.e. 365 days and the production of GHGs per biomass, the total GHG production from the yellow mealworms can be found:

$$\begin{aligned}\text{total N}_2\text{O production by yellow mealworm larvae} &= 69\,\frac{\text{mg N}_2\text{O}}{\text{kg biomass \& year}} * 365\,\frac{\text{days}}{\text{year}}\\ &\quad * 1\,000\,000 \text{ kg yellow mealworm biomass} * 10^{-6}\,\frac{\text{kg}}{\text{mg}}\\ &= 548\,\frac{\text{kg N}_2\text{O}}{\text{year}}\end{aligned}$$

A.3.2 Wastewater

Yellow mealworm

According to Thévenot et al. (2018), 2.538 kg of raw sewage sludge is produced per 1 kg of insect meal from the yellow mealworm larvae, which means that from the production of yellow mealworms, the total amount of raw sewage sludge produced per year is:

$$\begin{aligned}\text{total amount of raw sewage sludge from yellow mealworm production} &= 2.538\,\frac{\text{kg raw sewage sludge}}{\text{kg meal}}\\ &\quad * 177\,510\,\frac{\text{kg meal}}{\text{year}}\\ &= 450\,521\,\frac{\text{kg raw sewage sludge}}{\text{year}}\end{aligned}$$

Black soldier fly

Smetana et al. (2019) reports of 227.72 L of wastewater produced per 1 kg meal produced, which gives a total annual wastewater production of:

$$\begin{aligned}\text{total wastewater from BSF production} &= 227.72\,\frac{\text{L wastewater}}{\text{kg meal}} * 765\,741\,\frac{\text{kg meal}}{\text{year}}\\ &= 174\,374\,612\,\frac{\text{L wastewater}}{\text{year}}\end{aligned}$$

Note that for the yellow mealworm, the wastewater is reported to be in the form of sewage sludge, which requires extensive treatment to limit adverse effects on waterbodies. This process does as such not recycle any water back into nature. For the BSF, however, the residual from water use is reported to be wastewater, which can be treated in a wastewater treatment facility before most of it can be returned to nature. This demonstrates a clear difference between the two systems.

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