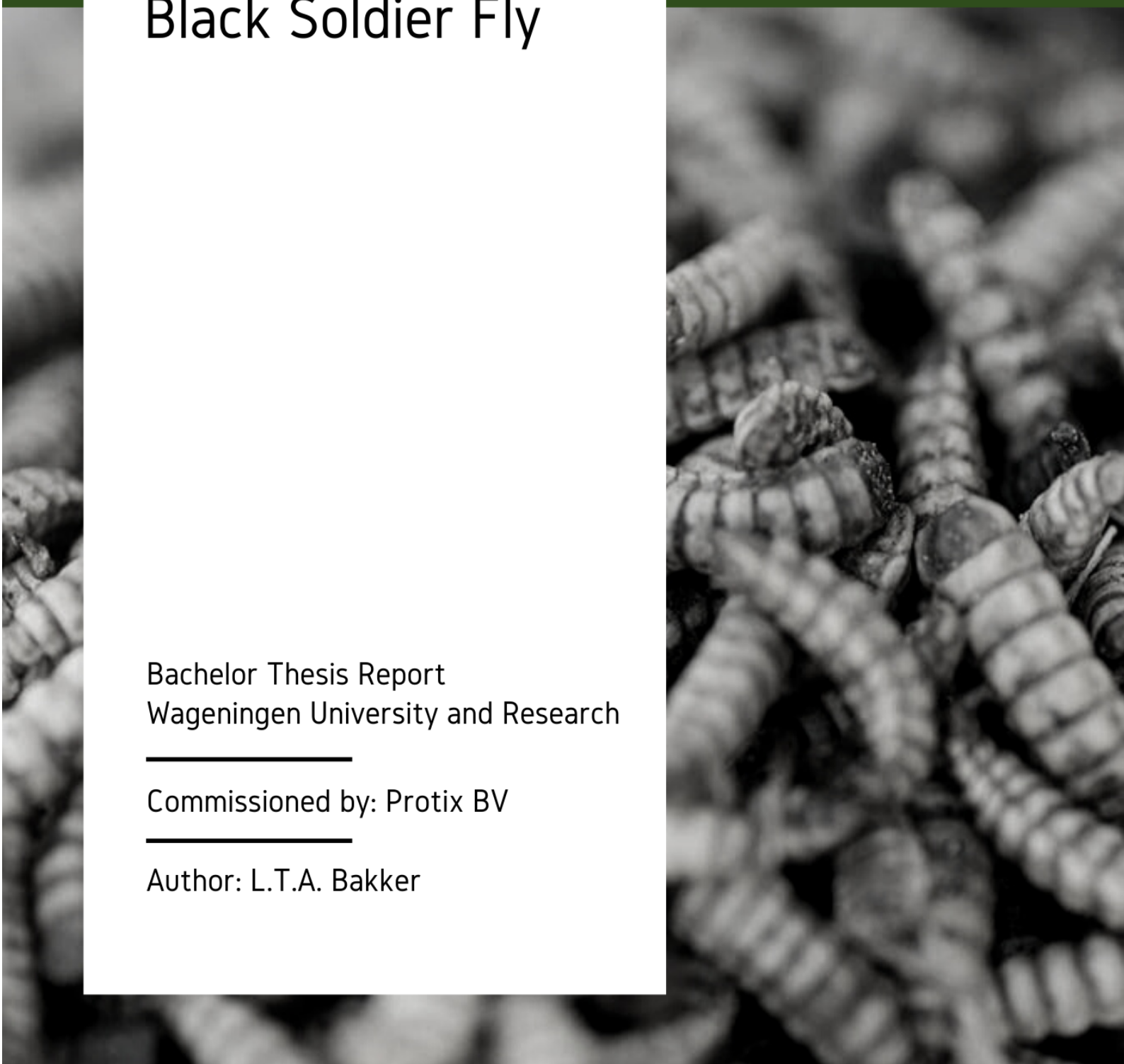
BACHELOR THESIS REPORT

Product market applications of the Black Soldier Fly



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A literature study on the product market applications of the Black Soldier Fly

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Abstract

The aim of this study was to gather insight in the current and future product market applications of the larvae of the black soldier fly (BSF). A combination of systematic and non-systematic literature review has been used to gather these insights.
The BSF is an insect with lots of potential, it has a short life cycle, is fast growing and it is able to convert low value organic waste, into high value marketable ingredients. These high value marketable ingredients are whole BSF meal, extracted protein meal, extracted oils and various by-products. These ingredients do have characteristics that are similar to traditional, in some cases less sustainable ingredients in products on various markets. Currently products of the BSF are applied into the fish feed, livestock feed, pet food, fertilizer and bio diesel. However, all market shares of current products containing BSF on those markets are very small. Additionally, research shows positive effects regarding the consumer food, livestock protein, pharmacy and cosmetics market as product market combinations in the future. In order for the industry to sustain in the future, technological developments need to stimulate production and lower the prices, legislation needs to open markets, consumer acceptance needs to rise, and research needs to stimulate future product market applications.

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1. Introduction

1.1 Background

According to the United Nations human population and global welfare are increasing (United Nations, 2019). This causes a growing demand for food and feed worldwide. The Food and Agriculture Organization of the United Nations (FAO) estimated that the total demand for agricultural products will be sixty percent higher by the end of 2030 compared to the demand in 2013. Besides, environmental change is putting pressure on the current global food system (Van Huis et al., 2013). These developments cause a global growth in demand for (sustainable) proteins and other high value ingredients for as well humans as animals. Insects contain high value components like proteins and oils, which can be used as an alternative or addition to more traditional protein and oil sources (Van Huis et al.,2013). Insects are a good and more sustainable alternative for traditional proteins like for example soybean, which is mainly imported from countries in South America. Insects are able to grow on waste streams and have a high feed conversion efficiency (Rumpold & Schlüter, 2013; Van Huis et al., 2013). Other positive aspects of insects are that insect rearing is not land-based, and thus does not require a lot of land use, it has a relatively low GHG emission and it requires less water compared to other protein sources (Muller, Wolf & Gutzeit, 2017; Van Huis et al., 2013).

Currently, almost two billion people all over the world include insects as part of their diet. This so-called "entomophagy", the consumption of insects by humans, is not very common in the western culture, and mainly occurs in tropical countries (van Huis et al., 2013; van Huis, 2020). The current western insect industry is mainly represented by small and medium-sized companies. A lot of these companies are start-ups; only a few are long established companies. The companies that have been around for a longer period of time mainly supply hobby-pet shops and zoos to feed reptiles and amphibians. The start-ups are supplying the newer markets and originate mainly from the last decade (Halloran, Flore, Vantomme & Roos, 2018). These companies mainly produce insects for food and feed (Halloran et al., 2018; Van Huis, 2020).

Currently, the black soldier fly larvae, hereinafter called BSF, as an insect is very popular. One of the main advantages of the BSF compared to other insects is that it is the most efficient insect in bio converting low quality organic waste (Diener, S., Solano, N., Roa-Gutiérrez, F., Zurbrügg, C. & Tockner, K., 2011; Hilkens & de Klerk, 2016; Lundy & Parrella, 2015). Research shows that the BSF is even able to convert catering waste and manure (Zhang et al, 2020). However, in the western world it is not allowed to use BSF grown on these waste products. (Van Huis, 2020). The BSF consists of proteins and oils and can be used for multiple purposes, including food, pet food and animal feed. In addition, it can also be applied in products for industrial and pharmaceutical purposes (De Smet, Wynants, Cos & Van Campenhout, 2018; Rumpold & Schlüter, 2013). Eventually, leftover by-products and substrates of the BSF can also be used as fertilizer or as biogas (Putra, Hutami, Suantika & Rosmiati, 2017). Currently, it is allowed to use BSF proteins as pet food, fish feed and human food when reared on organic waste streams. However, it is not allowed to feed livestock with insect proteins yet. On the other hand, insect-derived fats are allowed, as well as live insects. It is expected that in the next few years it will be allowed to use insect proteins in livestock feed (Van Huis, 2020).

Knowledge gap

This research aims to answer a knowledge gap. Pre-research by a search query has been conducted in order to get insight in the knowledge gap. The query (table 1) has been formulated using the main concepts of this research and resulted in 1841 documents in Scopus. These documents have been screened; this screening process is shown in a PRISMA diagram which can be found in appendix 1. The screening process resulted in articles relevant for this research. However, zero of these articles gave an overview of current product market applications of the BSF. The articles found where specific on

marketable ingredients, products, markets or related to a specific country. These articles are relevant to analyze during this research. However, to the best of the authors knowledge, there is no overview review study or meta study article available about all current product market applications of the BSF.

Concepts	Search Terms
Black Soldier Fly	("black soldier fly" OR BSF OR "hermetia illucens linnaeus" OR "hermetia illucens" OR "zwarte soldaat vlieg")
Current	**AND** (current OR present OR existing OR available OR huidig OR bestaand)
Product market applications	**AND** ("product-market applications" OR PMC OR "product-market strategies" OR "product market combinations" OR "product applications" OR "market applications" OR products OR markets OR "product-market combinaties")

Table 1. Search Query pre-research

There has been chosen to study the knowledge gap about the current available product market applications, since applying the search query showed that there is no overview study which shows all product market applications possible for the BSF. To study the current product market applications of the BSF, the following central research question was formulated: "*What are the current product market applications of the black soldier fly larvae?".*

To be able to answer the research question, the following sub-research question have been formulated:

1. What kind of marketable ingredients does the black soldier fly consist of?
2. What are the current and future product market applications of the proteins of the black soldier fly?
3. What are the current and future product market applications of the oils of the black soldier fly?
4. What are the current and future product market applications of the by-products of the black soldier fly?

However, during research it became clear that research not only shows the current product-market applications, but also the possible future market applications. Due to this, the central research question has been changed to: "*What are the current **and future** product market applications of the black soldier fly larvae?".*

To be able to answer the new research question, the following (new) sub research questions have been answered in this research.

1. What kind of marketable ingredients does the black soldier fly consist of?
2. What are the current product market applications of the marketable ingredients of the black soldier fly?
3. What are the future product market applications of the marketable ingredients of the black soldier fly?
4. What are the key drivers for the future of the current and future product market applications of the black soldier fly?

Reading guide

This report will provide insights into the current and future product market applications of the BSF. Initially, key concepts and definitions will be described in paragraph 1.2, followed by paragraph 1.3 in which the methodology used in this research is described. After, the results will be shown starting from chapter 2, in which sub research question 1, "*What kind of marketable ingredients does the black soldier fly consist of?"* will be answered. In

chapter 3, sub research question 2, "*What are the current product market applications of the marketable ingredients of the black soldier fly?"* will be answered. followed by chapter 4, which will give an answer on sub research question 3, "*What are the future product market applications of the marketable ingredients of the black soldier fly?"* To make an outlook for the future, chapter 5 will answer sub research question 4, "*What are key drivers for the future of the current and future product market applications of the black soldier fly?",* by applying a PESTEL-analysis, in which the key drivers for change will be presented. Finally, a conclusion and discussion will give an answer on the central research question, discuss the results and give some limitations and recommendations for further research.

1.2 Key concepts and definitions

In this chapter the key concepts and definitions regarding the central research question and the sub-questions will be described. The definitions of the key concepts will be explained using literature.

Current

This term is strongly related to the concept "product market applications" since the research question is about current and future product market applications. According to the stages of the industry life cycle created by Porter in 1980 (figure 1) the current insect industry is now in the growth phase. At this moment there is high growth in the industry, it attracts various market segments and the profitability starts to raise.

In this research current product market applications are defined as product market applications which are beyond Technology Readiness Level (TRL) nine for at least one year at February 2020. The nine level TRL system (appendix 2) was developed by John Mankins in 1995 for the National Aeronautics and Space Administration (NASA). TRL nine is the last stage in this system and means that all technologies being applied in the actual systems go through TRL nine (Mankins, 1995). This means that after TRL 9, a product market application is a commercial product market application for at least one year before the moment of doing research. There has been chosen for a time period of one year because it is allowed by the European Union to feed farmed fish with animal proteins since July 2017 (TSE-regulation (EC) 999/2001), this includes insect proteins (Regulation (EU) 2017/893). This means that a lot of product innovations origin from the latest 3 years and making the time period stricter would not include those innovations.

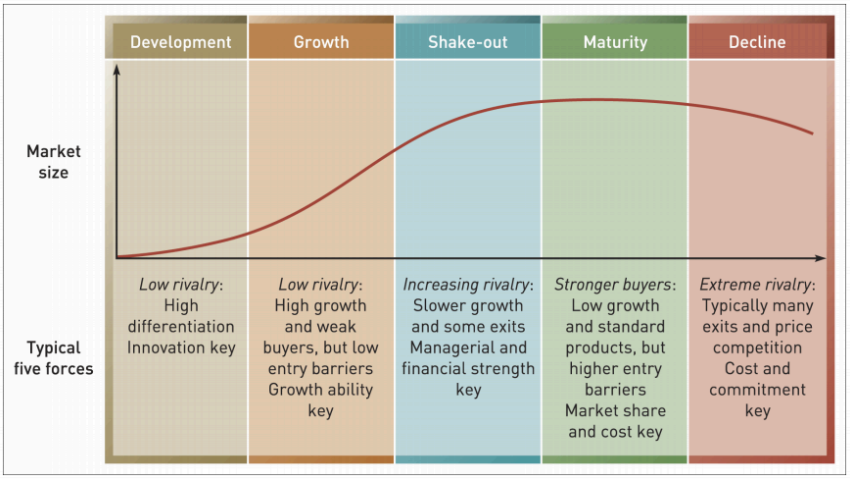

Figure 1. Industry Life Cycle (Johnson, Whittington, Scholes, Angwin & Regnèr, 2017).

Future

This term is strongly related to the concept "product market applications" since the research question is about current and future product market applications. The Oxford dictionary describes the concept future as: *"the future [singular] the time that will come after the present or the events that will happen then". (Oxford Dictionary, 2020).* In this research current product market applications will be described as possible product market applications that can be put on the market in the future.

Product market application

According to Johnson et al. (2017), a market is a group of customers for specific products or services that are essentially the same. For this research, not only the end customer of the certain products (B2C) will be kept in mind, but also the strategic customer of the BSF producer will be kept in mind (B2B). For the producer the consumer is not the one at whom their strategy is primarily addressed, BSF's can be used as a product application into multiple products and be sold on various markets, also as a semi-finished product. Since

the BSF is a versatile product containing various usable ingredients, for this research product market applications for both B2B as B2C will be analyzed.

1.3 Methodology

To be able to answer the central research question, "*What are the current and future product market applications of the black soldier fly larvae?"*, a combination of a systematic and non-systematic literature review has been conducted. This chapter will give an overview of databases used, the search queries that have been used in order to conduct the systematic literature review and the method of non-systematic literature review will be explained. Besides it will describe the way the literature is analyzed.

Databases

The scientific (peer-reviewed) articles have been gathered by applying relevant search terms, using Scopus, Web of Science and WUR Library. Scopus and Web of Science are bibliographic databases that have a quality check for indexing journals, this means that literature retrieved from these databases is most reliable. WUR Library does not have these quality checks. However, WUR Library has been used to gather access to literature which was found but not accessible via Scopus and Web of Science.

Search Queries

To find suitable literature to be able to answer the research questions, search queries for each sub research question have been formulated. Since various researchers use different words for the same main concepts, synonyms have been formulated. To be able to apply synonyms and to combine multiple concepts, the following so-called *Boolean* operators haven been used (Cooper, Schindler, Blumberg, 2014):

- [AND] operators have been used to narrow the search terms and combine two different concepts.
- [OR] operators have been used to broaden the search terms with synonyms.

Besides, parentheses have been used to indicate the order in which the database should process the operators.
Also, symbols like "*" have been used, to search for word variations.

To be able to answer the initial central research question, search queries for each initial sub research question has been formulated. These search queries are shown in table 2, 3, 4 and 5. The search queries have been applied in a systematic way, by application in Scopus, and screening the results. The screening processes are shown in PRISMA diagrams which can be found in appendix 3. It shows the number of papers identified through search, records after applying inclusion criteria and records screened in excel. Besides, it shows which papers were excluded after screening in excel based on accessibility, content, and relevance for another sub-question. After all, it shows the final set of articles included in the review.

Sub research question 1

For research question 1, "*What are the current and future product market applications of the proteins of the black soldier fly?"* the query (table 2) resulted in 1749 documents in Scopus, of which in total 1485 documents were excluded applying inclusion criteria. Main part of these documents, namely 1167, were excluded because of the subject area. After the first screening, 264 results were screened in Excel, by reading the title, and if relevant the abstract. The second inclusion resulted in a total of 16 documents which have been reviewed in order to answer sub research question 1. The complete analysis can be found in the PRISMA diagram in appendix 3.1.

Concepts	Search Terms
Black Soldier Fly	("black soldier fly" OR BSF OR "hermetia illucens linnaeus" OR "hermetia illucens" OR "zwarte soldaat vlieg")
Genes	**AND** (gene* OR DNA OR biology)
Other:	**AND** (LIMIT-TO (DOCTYPE, "ar" OR "re"))
	AND (LIMIT-TO (SUBJAREA, "BIOC"))
	AND (LIMIT-TO (LANGUAGE, "English"))

Table 2. Search query sub research question 1

Sub research question 2

The search query of initial research question 2, "*What are the current and future product market applications of the proteins of the black soldier fly?"* is showed in table 3. This query resulted in 2344 results in Scopus. During the first screening step 1768 documents were excluded, mainly because the subject area was not relevant. Afterwards 576 documents were screened in excel, of which 544 were excluded because the content was irrelevant. The second screening resulted in a final set of 20 documents. The complete analysis can be found in the PRISMA diagram in appendix 3.2.

Sub research question 3

The search query of initial sub research question 3, "What are the current and future product market applications of the oils of the black soldier fly?" is showed in table 3. The query resulted in 952 records through Scopus search. During the first screening step 516 documents were excluded, mainly because the subject area was not relevant. Afterwards, 436 records were screened in excel of which 399 documents were excluded because the content was irrelevant. This resulted in a final set of 16 records. The complete analysis can be found in the PRISMA diagram in appendix 3.3.

Concepts	Search Terms
Black Soldier Fly	("black soldier fly" OR BSF OR "hermetia illucens linnaeus" OR "hermetia illucens" OR "zwarte soldaat vlieg")
Product market applications	**AND** ("product market applications" OR PMC OR "product-market strategy" OR "product market combinations" OR "product application?" OR "market application?" OR products OR markets OR "product-market combinaties")
FOR Proteins	**AND** (protein*)
FOR Oils	**AND** (oil* OR oil* OR fatty acid OR fat*)
Other:	**AND** (LIMIT-TO (DOCTYPE, "ar" OR "re"))
	AND (LIMIT-TO (LANGUAGE, "English"))

Table 3. Search query initial sub research question 2 and 3

Sub research question 4

Initial sub research question 4, *"What are the current and future* product market applications *of the by-products of the black soldier fly?",* resulted in a total of 899 records by applying the search query in Scopus (table 4). The search query of sub research question 4 is more specific, since previous, less specific search queries, led to only a few relevant articles. After first screening, 438 documents were excluded, mainly based on subject area. Afterwards in the screening in excel another 446 documents were excluded mainly based on content. This resulted in a final set of 15 documents. The complete analysis can be found in the PRISMA diagram in appendix 3.4.

Concepts	Search Terms
Black Soldier Fly	("black soldier fly" OR BSF OR "hermetia illucens linnaeus" OR "hermetia illucens" OR "zwarte soldaat vlieg")
Product market applications	**AND** ("product-market applications" OR PMC OR "product-market strategy" OR "product market combinations" OR "product application?" OR "market application?" OR products OR markets OR "product-market combinaties")
By products	**AND** (by-product* OR "by product*" OR residual* OR residue OR "residue products" OR manure OR waste)
Specific by-products	**AND** (chitin OR biogas OR biodiesel OR fertilizer* OR pharma* OR medicin* OR cosmetic*)
Other:	**AND** (LIMIT-TO (DOCTYPE, "ar" OR "re"))
	AND (LIMIT-TO (LANGUAGE, "English"))

Table 4. Search query initial sub research question 4

From the analysis in the PRISMA diagrams there can be concluded that most of the articles have been excluded by the subject area, most of them where not relevant for social sciences and focused mainly on technical research. Besides, it showed that not only relevant literature has been found by the search queries used for a certain sub question, but also by other sub questions. These have also been included in the literature review of that sub question.

Non-systematic research
Besides systematic research, non-systematic research has been applied. Non-systematic research is an informative, in-depth research, but does not aim to gather all information available (Cooper et al., 2014). For example, there has been searched for literature outside the search queries if there was a need for specific, more in-depth information on a certain topic. For example, Web of Science has been used to search for more in-depth information on BSF and animal feed. Besides, non-systematic research has been used to gather information for new research question 4, "*What are the key drivers for the future of the current and future product market applications of the black soldier fly?"*. Non-systematic research has been used to specifically search for information related to the PESTEL analysis.

Furthermore, snowballing has been applied. By snowballing cited articles by a relevant article have been consulted in order to find more relevant information (Jalali & Wohlin, 2012). When relevant articles have been found using the search queries, other related articles can be found using snowballing. This method has been applied because more in-dept information was needed on topics in this research.

Evaluating the literature
The relevant literature has been reviewed structurally. First the abstract and table of content have been evaluated, to get an idea of the structure and relevancy of the research. Afterwards, the introduction has been read to get an idea of the purpose and relevance of the research. Finally, the relevant chapters, discussion and conclusion have been read and scrutinized. Afterwards, the relevance and quality have been evaluated by applying the checklist prepared by the Wageningen University literature reviewing module. After evaluating, relevant literature is synthesized by comparing and facing various sources and identifying similarities and differences.

2. The Black Soldier Fly

In this chapter, sub research question 1, *"What kind of marketable ingredients does the black soldier fly consist of?"*, will be answered using literature. In paragraph 2.1 it will give an overview of the live cycle and most important characteristics of the BSF; besides it will give an overview of the organic waste products the BSF is able to convert during its larval stage. In paragraph 2.2 it will discuss the marketable ingredients of the BSF, namely whole BSF meal, protein meal, the oils and by-products. The chapter will be closed by a conclusion in paragraph 2.3.

2.1 Live cycle of the Black Soldier Fly

The life cycle of the BSF has four phases: the egg stage, larval stage, pupa stage and adult stage (Li, Zheng, Qiu, Cai, Tomberlin & Yu, 2011) (figure 2). The *Black Soldier Fly (BSF),* scientific name *Hermetia illucens (Linnaeus),* originates from tropical and subtropical regions, and it prefers temperatures around 28-32 °C (Hilkens & de Klerk, 2016; Müller, Wolf & Gutzeit, 2017). The eggs of the BSF are about 1 mm in length and turn into a larva in approximately 4 days (Diclaro & Kaufman, 2015). It takes the larva 14 days to fully develop (Hall & Gerhardt, 2002). In its larval stage, the BSF is able to convert organic waste into larval biomass, which is of high quality and in rough form contains approximately 40% proteins and roughly 30% fats, based on dry matter. (Diener, Zurbrügg & Tockner, 2009; Makkar, Tran & Ankers, 2014). When fully developed, the larva can be 27 mm in length and 6 mm in width (Diclaro & Kaufman, 2015). After 14 days, the larva seeks for a dry place and pupates, pupation takes another 14 days in general (Hall & Gerhardt, 2002). Next, the BSF is in its adult stage. In this stage is about 20 mm in length. It is not able to eat in the adult stage since it lacks functional mouthparts, it is only able to drink water in this stage. This means that it completely relies on the nutrients and fats stored in the larval stage (Banks, 2014; Bruno et al., 2019 Tomberlin & Sheppard, 2002). The adult BSF lives for about 7 days in general. In this period, the female BSF needs to find a male BSF to mate. After mating, the female BSF deposits about 500 eggs in general (Diclaro & Kaufman, 2015).

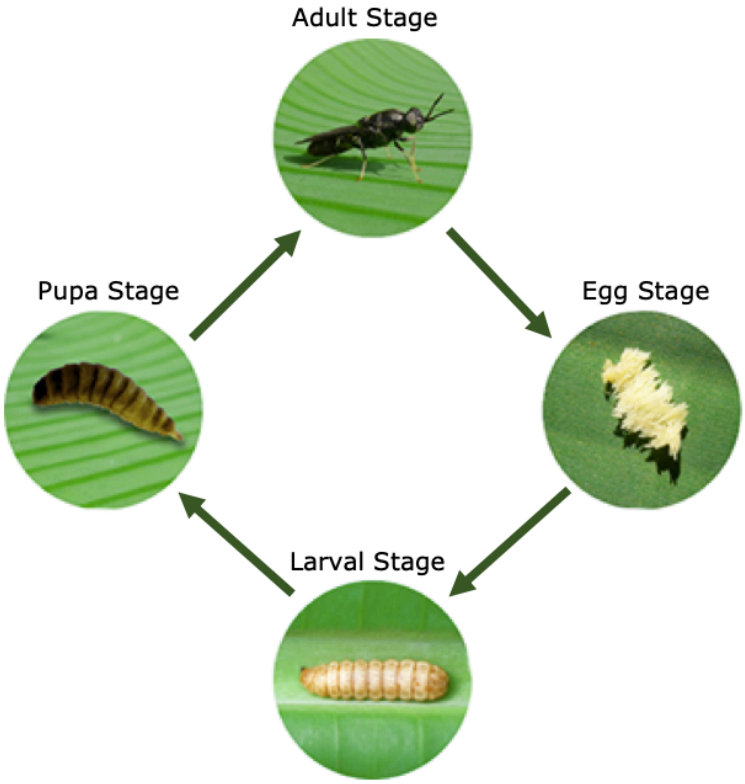

Figure 2. Live cycle BSF (Entofood, 2016)

Organic waste conversion

Research showed that the BSF is very efficient in converting various products of organic waste. The BSF is able to convert catering waste, which contains various products from meat to vegetables and manure. It is even able to convert (fish) offal (Newton, Sheppard, Watson, Burtle & Dove, 2005; St-Hilaire, 2007; Zhang et al., 2020). However, in the western world it is not allowed to use the BSF grown on these waste materials on a marketable product (Van Huis, 2019). Although, it is allowed to use BSF in various product market applications when fed with other organic waste materials, like fruit & vegetable

waste. However, also other organic food wastes like coffee residues can be used as organic waste (Diener et al., 2009; Nguyen, Tomberlin & Vanlaerhoven, 2015). There can be concluded that the BSF is able to grow on various organic waste products, however, to be marketed in western countries, it is not allowed to rear BSF on residues containing animal protein or manure.

2.2 Marketable ingredients

The BSF can be marketed in various stages and substances. This paragraph will give the characteristics of the marketable ingredients of the BSF larvae, separated as whole BSF meal, defatted protein meal, the oil fraction and its various by products.

Meal of whole BSF

The BSF can be marketed whole dried and processed into meal with a dry matter content of about 95% (Veldkamp et al., 2012). By this process the oil content of the BSF is not separated from the protein content. Since the product is not defatted, the protein content of this product is about 40% and the dried oil content varies, but is on average 30% (Caligiani et al., 2017; Diener, Zurbrügg & Tockner, 2009; Lie et al., 2017; Makkar, Tran & Ankers, 2014; Muller et al., 2017).

Protein meal

The protein content of the BSF larvae can be processed and separated from the oil fraction. When defatted, protein meal of the BSF can have protein values over 60 % (Spranghers et al., 2017). The protein is made up of amino acids. The amino acid composition of the BSF is, in rough form, very similar to the protein content of soybean meal. (Maurer et al., 2016; Spranghers et al., 2017). The exact amino acid composition of the BSF is relatively constant when reared on organic waste streams (Spranghers et al., 2017).

Oil fraction

The BSF larvae can be processed and oil fraction can be separated from the protein fraction. In contrast to the stable protein component of the BSF, the oil content can be highly variable, it can vary between 15% and 49% depending on the substrates the BSF grew on (Caligiani et al., 2017; Makkar, 2014; Spranghers et al., 2017). Research showed that the lowest values are reached when feeding BSF with poultry manure (Arango Gutierrez, Vergara Ruiz, Mejia Velez, 2004) and highest value by BSF fed with oil rich food (Barry, 2004; Muller et al., 2017). The oil part of the BSF is a complex combination of elements. The main part of the oil is the fatty acid lauric acid and its esters. Lauric acid is also one of the main components of coconut oil (Dayrit, 2015; Ushakova et al., 2016).

By-products

The BSF contains other high quality, valuable bioactive substances which remain after rearing and after proteins and oils are extracted from larval mass (Kim et al., 2011; Müller et al., 2017). The exact percentage of these by-products depends on the exact oil and protein content of the BSF. After extracting proteins and oils from the BSF, enzymes, like ligninases and cellulases, which are among other things, used by the BSF to process cellulose, remain (Müller et al., 2017). Besides, the BSF contains chitins and anti-bacterial peptides. Chitins are a polysaccharide, which primarily contains acetyl glucosamine sugar moieties. By a chemical process, alkaline deacetylation, the sugar chitosan can be extracted. Furthermore, various studies have showed that the BSF contains antimicrobial peptides, which are for example valuable as antibiotics (Choi, Yun, Chu & Chu, 2012). Besides, BSF also contains other by-products, namely the residue products which are released after rearing. This includes mainly excrements, residues of organic waste, and BSF skins (Müller et al, 2017).

2.3 Conclusion

The literature review in this chapter is conducted in order to answer sub research question 1, *"What kind of marketable ingredients does the black soldier fly consist of?"*.

There can be concluded that the BSF is an insect with a short lifetime and a fast-growing cycle. It is able to convert organic waste products into high value marketable ingredients. One of these marketable ingredients is whole BSF meal; a whole BSF processed into a meal product. Besides, the BSF can also be extracted and separated, a defatted protein meal with a protein content up to 60% and an extracted oil part of on average 30%, remain. The protein part of the BSF mainly consists of amino acids and is comparable to soybean meal. The oil part of the BSF mainly consists of lauric acid, which is also one of the main components of coconut oil. When extracting the oil and protein part of the BSF, some by-products are released. These by-products mainly consist of enzymes, chitins and antimicrobial peptides. Additionally, after rearing, residue by-products remain. The residue mainly includes excrements, residues of organic waste and BSF skins.

3. Current product market applications

In this chapter, sub research question 2, "*What are the current product market applications of the marketable ingredients of the black soldier fly?*", will be answered using literature. In the individual paragraphs, it shows a review on literature about current applications on the fish feed market, livestock feed market, pet food market and applications as fertilizer and bio diesel. It will also give a review on current market numbers. These product market applications are discussed because these are on the market for at least one year. The chapter will be closed by a conclusion.

3.1 Fish feed market

Traditionally, farmed fish are fed with fish meal or soybean meal. However, the application of these ingredients is discredited in recent years (Stamer, 2015). This paragraph gives a review on the literature available on the current product applications containing BSF on the fish feed market.

Traditional fish feed

In nature, insects are one of the natural feed sources for carnivorous and omnivorous fish (Henry, Gasco, Piccolo & Fountoulaki, 2015). Fishes need high values of protein content, ranging from 30 to 55 percent dry matter (Henry et al., 2015; Wilson, 2003). Because fish need a high protein content in their feed, fish meal made of wild fish, has been the main component of farmed fish feed (Nogales-Merida et al., 2018). However, using fish meal as a source to feed fish has some limitations. Because of the growing consumption, since 2014, more farmed fish is consumed compared to caught fish (FAO, 2016). More than 90% of the caught fish is used to process into fish meal to feed farmed fish, this leads to negative effects on the natural fish population in oceans, which leads to a limited availability of fish meal to feed farmed fish (Stamer, 2015).

Due to these developments, the use of soybean meal to feed farmed fish has become popular (Stamer, 2015). However, because of the growing demand of soybean for consumption and other purposes, soybean meal is getting more expensive, which is a disadvantage of soybean meal for fish feed (Nogales-Merida et al., 2018; Stamer, 2015). Another disadvantage of soybean meal is that it is not a sustainable alternative for fish meal, since it uses a high amount of energy and water for its production (Naylor et al., 2009). From here it can be concluded that there was and is a need for an alternative for fish meal and soybean meal in fish feed. Now whole insect meal is seen as an alternative for fish meal and soybean meal in fish feed (Nogales-Merida et al., 2018).

Whole BSF meal in fish' diets

Multiple researches have been conducted regarding the partly or total replacement of fish meal by whole BSF meal. Seven of these studies stand out.

In first and second researches, sensory tests have been conducted on the total or partial replacement of fish meal with whole BSF meal in the diets of Salmon. Both of these studies found no differences in performance of the fish and fish quality (Belghit et al., 2019; Lock, Arsiwalla, & Waagbø, 2016).

Third study by Guerreiro et al. (2019) has been conducted on the suitability of whole BSF meal as a replacement for fish meal in the diets of meagre (also called stone sea bass). This study recommended to replace 17% of fish meal with 10% of whole BSF meal to get similar effects and fish quality.

Fourth study, a case on zebrafish, partly replaced fish meal with whole BSF meal. This experiment showed that fish meal can be replaced with at least 25% whole BSF meal without having any negative consequences (Zarantoniello et al., 2019).

In the fifth study, no significant differences were found by replacing 25% of the fish meal with whole BSF meal in the diet of yellow catfish (Xiao et al., 2018).

Sixth study, in which the diet of seabream was substituted with whole BSF meal at various percentages, showed no negative effects on feed conversion ratio or performance. However,

it led to significant lower growth rates compared to seabream fed with fish meal. (Karapanagiotidis et al., 2014).
Similar results were found in the seventh study, where fish meal in the diets of turbot was replaced with whole BSF meal; turbots showed a significantly lower growth rate when fed with whole BSF meal compared to fish meal (Kroeckel et al., 2012).
Besides, an experiment on feeding shrimp, a crustacean, with a component of whole BSF meal, showed no major differences in growth and quality by replacing fish meal with 25% of BSF meal (Cummins et al., 2017).

There can be concluded that it is possible to replace fish meal and soybean meal in fish feed totally or partly with whole BSF meal. However, it is not possible for all fish species. There are differences between species regarding the effects of replacing fish meal with whole BSF meal. Nevertheless, it can be concluded that a total replacement is possible for salmon and a partial replacement for the meagre, zebrafish, yellow catfish and shrimps.

Product applications
Since July 2017 it is allowed to feed farmed fish with feed that includes animal protein (like BSF protein) in the European Union (TSEregulation (EC) 999/2001) regulation (EU) 2017/893). In Canada it is allowed to include whole BSF meal in fish feed since 2012 and also in Australia it is allowed to feed fish with insects (Lähteenmäki-Uutela et al., 2017). In other western countries additional request or legislation is needed.

There are multiple products on the professional fish farming feed market, one of these products is produced by Protix and is called "friendly fish". This product contains whole BSF meals for Salmon, Trout and Shrimp. Protix provides these supplements to bigger fish feed players in the market. The current global aquafeed market was worth 69 billion US dollar in 2018 and has a compound annual growth rate of 7.5%. However, due to the limited availability of BSF and the big market values, the percentage of fish meal including insects and BSF is, according to various experts at Protix, negligible at this moment.

To summarize; since fish meal and soybean meal are unsustainable types of fish feed, there was and is need for an alternative. Whole meal of the BSF is able to partly or totally replace fish meal in diets of salmon, meagre, zebrafish, yellow catfish and shrimps. Due to regulation it is allowed to feed fish with BSF meal in Canada since 2012 and in the EU since 2017. Currently the product whole BSF meal is applied into the market of fish feed. Due to this, this is a current product market application. However, due to the current limited availability of whole BSF meal on the market, current market value of BSF meal for fish is negligible.

3.2 Livestock feed market

Currently, soybean oil is included in the diets of livestock. Due to the environmental disadvantages of this kind of oil, an alternative is needed (Naylor et al., 2009). This paragraph shows a review on the literature of the currently available products including BSF on the livestock feed market for poultry and nursery pigs. It focuses on the BSF oil and live BSF larvae since it is allowed to feed livestock with live insects, insect oils or hydrolyzed insect protein only.

BSF oils in broiler chickens' diet
Three researches conducted an experiment with the replacement of soybean oil by BSF oil in the diets of broiler chickens. All three researches found no significant difference in performance or meat quality when completely replacing soybean oil by BSF oil in broiler chickens' diets (Benzertiha et al., 2019; Kierończyk et al., 2020; Schiavone et al., 2016). One of the researches even found promising results in decreased fat content in the liver and total cholesterol value of the chickens (Benzertiha et al., 2020). Another research by Sypniewski et al., (2020) into young turkeys showed that it is also possible for other Galliformes to totally or partially replace soybean oil by BSF oil is applicable without having

negative effects. It even showed that it can even be considered an antimicrobial fat (Sypniewski et al., 2020).

BSF oils in nursery pigs' diet
Regarding BSF oils in pigs' diet, one experiment has been found. This experiment by Van Heugten, Martinez, McComb, and Koutsos (2019), showed that BSF oil is a valuable product for nursery pigs. It concluded that adding BSF oil at a maximum percentage of 6% to the diets of 21-day old pigs, replacing corn oil (another replacer of soybean oil), has positive effects on the nursery pigs. The experiment did not show any negative effects and it even improved growth performance of the pigs.

Live BSF larvae in laying hens' diet
Besides feeding oil of the BSF to (broiler) chickens, it is also able to provide laying hens with live BSF larvae (Star et al., 2020). A research by Star et al. (2020), shows that, feeding live larvae to the chickens, stimulates natural behavior, since chickens consume larvae's in nature. Free-range chickens spend for about 40% of their time searching for and eating insects (De Vries, 2000). This helps to solve welfare issues among chickens in current farms, like feather pecking. However, it is not only a stimulus for natural behavior, the larvae are even nutritious for chickens (Star et al., 2020). The experiment concluded that it is possible to replace soybean meal with live BSF larvae supplemented with some additional local protein. It had no negative effects on production or performance of laying hens. It even had a positive effect on feather condition of the laying hens since feather pecking among the hens was decreased (Star et al., 2020).

Product applications
The Dutch feed compounder Coppens Diervoeding B.V., was the first worldwide to include insect oil in its chicken and pig feed and launched its products in 2016 (Hilkens & De Klerk, 2016; Plint, 2016). Protix currently has a concept providing live BSF to a certain poultry farmers' laying hens and selling the eggs to consumers under the brand name Oerei in supermarkets in the Netherlands since 2016 (Oerei, z.d.). According to research by Grand View Research (2019a), the total global poultry market value was over 175 billion US Dollar in 2018, with a compound annual growth rate of 4.5% till 2025. According to the same research agency, the global pig feed market was worth over 106 billion US Dollar with a compound annual growth rate of 3.5% (Grand View Research, 2019b). However, according to various experts at Protix, current market volumes including insects is very small and negligible in contrast to the total market, due to limited availability and legislation.

There can be concluded that BSF oil is a real alternative regarding soybean oil in diets of broiler chickens and nursery pigs. Besides, it is also possible to replace soybean meal in diets of laying hens with live BSF larvae completed with local proteins. Currently there is at least one feed compounder worldwide selling insect oils for chickens and pigs to farmers. Also, Protix is providing a farmer with living larvae, to be able to sell a unique egg concept of hens fed with living larvae, in supermarkets. Currently the product BSF oil is applied onto the market of pig and poultry feed, this is a current product market application. In addition, also live insects are applied onto the market of poultry feed, this is another current product market application. Despite the fact that BSF oil and live BSF are a real alternative regarding soybean meal and oil, current market volumes of livestock feed containing BSF are very small at this moment.

3.3 Pet food market

This paragraph shows a review on the available literature regarding the current available products including BSF on the pet food market. First discussing the hobby pet food market regarding reptiles and amphibians, and secondly discussing the current products on the cat and dog food market.

Products regarding reptiles and amphibians
Originally, insect production, mainly addressing live BSF and mealworms, is aimed at the hobby pet food market. This market includes reptiles, amphibians, birds and fish bait. Those animals consume insects in nature (Shelomi, 2020). The production companies who aim at those markets are the companies who are around for a longer period of time, and mainly supply hobby-pet shops and zoos. (Hilkens & De Klerk, 2016). However, this market is seasonal, in winter and autumn there is less demand, related to the breeding season of the birds and hibernation of the reptiles (Hilkens & De Klerk, 2016).

Whole BSF meal in cats' and dogs' diets
The biggest group hobby pets worldwide are dogs and cats, in 2018 there were about 470 million dogs and 370 million cats owned as pet worldwide (Bedford, 2018). Since hobby cats' and dog's main protein source is meat, it is estimated that the pet food industry, is responsible for about 25% of the environmental impact of the meat industry (Okin, 2017; Swanson et al., 2013). Research showed that the population of pet animals worldwide is rising (Lei, Kim, Park & Kim, 2019). Since the pet food industry competes for the same resources as other food and feed industries, the growing competition stimulates the development of new protein sources (Swanson, Yount, Aretz & Buff, 2013).

According to Hilkens and De Klerk (2016), insects are a good source of protein for specialty food for cats and dogs to replace (part of) the meat in pet food. Three experiments have been found regarding BSF in dogs' or cats' diets.
First experiment by Lei, Kim, Park and Kim (2019) showed that beagle dogs feed supplemented with 2% whole BSF meal had positive effects on the dogs: digestibility improved, and it showed anti-inflammatory and anti-oxidative effects.
Second experiment, published in the Italian Journal of Animal Science (2019), showed some signs that the digestibility of dog food containing whole BSF meal as protein source, was higher compared to dog food with traditional proteins, like meat (Russo et al., 2019).
Third experiment has been conducted regarding cats, traditional proteins in diets of cats were replaced with whole BSF meal. Research showed that main part of the cats in this experiment tolerated the food containing BSF, however the researchers recommend further research (Paßlack N. & Zentek J., 2018).

There can be concluded that research shows promising results regarding the partial replacement of traditional proteins in cats and dog food with BSF whole BSF meal. However, further research is needed in order to draw conclusions.

Product applications
Although the fact that not a lot of experimental records can be found about the supplementation of BSF, or insects in pet food in general, some pet food suppliers already have products in their assortment containing insects. Main part of the pet food containing BSF on the market claim the hypoallergenic characteristics of the BSF (Böhm, et al., 2018; Caligiani, 2017; Paßlack & Zentek, 2018).

According to an article by Market Line (2017), the company Netlaa BV, an English pet food producer launched the first hypoallergenic cat food brand containing BSF protein on the market in the Netherlands under the brand name "Trovet". Research on the internet learns that the brand has expanded in the last years and that it has multiple product ranges, including wet and dry food for pets containing BSF protein (Trovet, 2017). Besides Trovet, the company Protix sells two BSF product supplements to use as a supplement in pet food. These products are their ProteinX, a BSF protein meal, and PureeX, which contains both proteins and oils and is a supplement for wet pet food, Protix provides these supplements to pet food producers in the market (Protix, z.d.).

According to Jared Koerten, head pet care for Euromonitor International, in an article on Petfood industry.com, the total market value of pet food was over 91 billion US Dollar in 2018, showing a 6 % compound annual growth rate since 2013 (Phillips, 2019). However,

due to the big market values, the percentage of pet food including insects is, according to various experts at Protix, negligible at this moment.

To summarize, there is a need for alternative protein sources regarding cat and dog food. Research shows promising results regarding partial replacement of traditional proteins with whole BSF meal. Currently there are already some food products for cats and dogs on the pet food market containing whole BSF meal, that claim the hypoallergenic characteristics of the BSF. However, due to the fact that limited research is available and the fact that the pet food market is very big, products on the market containing BSF are very small at this moment.

3.4 Fertilizer

When rearing insects on (organic) waste substrates, residue product is generated. This residue product mainly includes excrements, insect skins and some organic waste residues that have not been eaten by the larvae (Müller et al., 2017). This paragraph shows a review on the available literature about the product application of the residues of the BSF on the fertilizer market.

Fertilizer is a product commonly used in agriculture. It is nutritious, helps (agricultural) products to grow faster, and it improves soil structure (Savci, 2012). Chemical fertilizers have been used in agriculture for a long period of time (Choi et al., 2009). However, chemical fertilizers have a big environmental impact quality (Choi et al., 2009; Savci, 2012). However, in order to be able to reach high agricultural productivity, fertilizer is needed.
Research by Choi et al. (2009), claimed that the compost remaining when rearing BSF, has for about the same quality as a commercial fertilizer product, but without having the negative aspects of being a chemical product. Another experiment showed that using the residue up to a percentage of 20%, is able to replace commercial fertilizer and leads to an increased growth of, in this experiment, baby leaf lettuce, basil and tomato (Setti et al., 2019). Since excrements and skins of BSF are category 2 and 3 material in the European Union (Regulation (EU) 2009/1069), it is only allowed to use these products as fertilizer or soil improver if it had a sterilization treatment at 70 degrees Celsius for one hour. This treatment is needed to make sure that the fertilizer does not include any weeds or pathogens.

The current traditional fertilizer market is worth over 155 billion US Dollar in 2019, with a compound annual growth rate of 3.8% until 2025 (Modor Intelligence, 2020). Currently there are some companies who sell BSF containing fertilizer on the market. In the USA there is a product called "insect frass" on the consumer market selling fertilizer containing BSF. In the Netherlands Protix is selling fertilizer under the brand name FlytilizerX, which is aimed at both B2B as B2C use (Protix, z.d.). The residue products of the BSF are currently sold on the fertilizers market. Thus, this is a product application of the BSF onto the fertilizers market. However, according to fertilizer specialist at Protix, current market volumes of all providing players worldwide are very small.

There can be concluded that the BSF rearing residue is very suitable as an organic fertilizer to replace chemical fertilizer. It is currently sold as a product on the market for both B2B as B2C. However, currently it still is a very small market.

3.5 Biodiesel

This paragraph shows a review on the literature available regarding possibilities of BSF to contribute to sustainable energy production by producing biodiesel.

Energy resources are very important for developed countries nowadays (Ishak & Kamari, 2019). However, currently mainly non-renewable fossil fuels are used for energy production. At this moment, biodiesel is a renewable alternative. The commonly used biodiesel is produced with vegetable oils. However, a disadvantage of the use of vegetable

oils as biodiesel, is that it competes with human food resources and agricultural land use (Ishak & Kamari, 2019; Li et al., 2011b). Besides, the BSF can also apply to biodiesel. Two experiments showed promising results. First experiment by Li et al. (2011), showed that the oil of the BSF, grown on various organic materials, like chicken manure, can fully replace rapeseed in the production of biodiesel without having negative aspects. The released biodiesel does even comply with the European biodiesel standards, EN14214. Similar results were found in the second experiment in which BSF were reared on restaurant kitchen waste. This study confirmed the applicability of BSF oil grown on low cost organic waste (Ishak & Kamari, 2019). Since excrements and skins of BSF covered by EU regulation 2009/1069 it is category 2 and 3 material, according to this regulation, it is allowed to use these products in biodiesel without treatment.

Although the fact that not a lot of experimental records can be found about the application of BSF in bio diesel, a lot of articles mention the possibility of it in their articles. Besides, currently in the literature it is unknown if this is used in the market, since when and by whom. However, experts at Protix mention that it is used nowadays, but exact applications and numbers are confidential information.

There can be concluded that it is possible to produce biodiesel by BSF oil to replace vegetable oil. The advantage of BSF oil over vegetable oil is that it does not compete with human food resources or agricultural land use. However, the market application is very small at this moment, and it is unknown if it is already done and by whom in literature.

3.6 Conclusion

The literature review of this chapter is conducted in order to answer sub research question 2, "*What are the current product market applications of the marketable ingredients of the black soldier fly?*". There can be concluded that there are various applications of the BSF products available on six markets.

First, the BSF is applied as a product onto the fish feed market. Five out of seven experiments related to the fish feed market, showed that whole BSF protein meal can be applied as fish meal to fully or partly replace fish meal and soybean meal in diets of certain fish species. Soybean meal and fish meal can be considered unsustainable types of (fish) feed.

Second, the BSF is applied as three products onto the livestock feed market replacing soybean products. From the articles reviewed there can be concluded that BSF oil is a suitable alternative to replace soybean oil in the diets of broiler chickens and nursery pigs. The articles even showed positive effects on the liver fat content of the broiler chickens and improved growth of nursery pigs. Besides, one experiment showed that it is possible to replace part of the soybean meal in diets of laying hens with live BSF. This application even had positive effects on pecking behavior among the hens.

Third, the BSF is applied as a product onto the pet food market. There is a need for alternative protein sources regarding cat and dog food, since they compete with proteins for human and animal consumption. Literature reviewed in this research shows that the BSF can be used to partially replace traditional proteins in cats and dog food. Among dogs even digestibility of the food improved.

Fourth, literature showed that the rearing residues of the BSF, containing mainly excrements, BSF skins and left-over organic waste, are very suitable to use as an organic fertilizer to replace chemical fertilizer.

Sixth, two experiments showed that BSF oil is able to replace vegetable oil in the production of biodiesel. An advantage of BSF oil over vegetable oil is that it does not compete with human food resources or land use.

All of the above-mentioned product market applications are sold on the market at this moment for at least one year. However, market shares of these products in the markets, are very small at this moment compared to the traditional products.

4. Future product market applications

In this chapter, sub research question 3, "*What are the future product market applications of the marketable ingredients of the black soldier fly?*", will be answered by a literature review. In the individual paragraphs it shows a review on the future possible product market applications of the BSF on the consumer food market, animal feed market, medicine market and cosmetics market. The chapter will be closed by a conclusion.

4.1 Consumer food market

This paragraph shows a review on the literature available regarding the future possible product applications containing BSF on the consumer food market.

Suitability of insects for human consumption

Since the world population is rising and sustainability is getting more important for consumers, alternative, more sustainable protein sources need to be found (Van Huis et al, 2013). Insects like the BSF can perform as an alternative for traditional proteins, since it has many environmental advantages over it; relatively low greenhouse gas emission and a higher feed conversion (Poma et al., 2017).

In some parts of the world, mainly China, Japan and Mexico, entomophagy exists for a long period of time (Van Huis et al., 2013). Multiple researches have shown that insects contain a suitable nutrient profile which meets the protein requirements for humans. It also contains fatty acids, and other valuable micronutrients valuable for humans (Rumpold & Schlüter, 2013; Tao & Li, 2018; Van Huis et al, 2013). According to research, the BSF is the most promising insect for human consumption due to its ability to convert waste and to transform it into high value proteins (Govorushko, 2019; Müller et al, 2017).

Consumer acceptance

Despite the fact that insects and the BSF have a lot of positive aspects for human consumption, consumer acceptance among consuming insects is low in the western world. Consumers be reminded of their childhood in which they were told that insects are disgusting and that you should not eat them (House, 2016). And, even in countries where insects have been consumed for ages, the consumption is declining due to developments of the country, consumers in those countries see insects as food for the poor (Sosa & Fogliano, 2017). According to research by Tao and Li (2018), a comparison can be made between consuming lobster and insects. Lobsters are now considered as a luxury dining product. However, in the 17th and 18th century, lobster was treated as junk food and known as food for prisoners. It is possible that insects will have the same potential as lobster in the future, since insects and shellfish are arthropods of the land and sea (Govorushko, 2019). Tao and Li (2018) propose that knowledge about positive aspects of insects among consumers is very important in order to achieve a change like happened with lobster. Megido and others (2014) suggest that the promotion of knowledge and acceptance of edible insects will begin with the understanding of the relationship between insects and shell- fish. Correspondingly, increasing the frequency of positive exposures and tasting trials would also be effective. Another aspect showing the potential of insects as food, is the fact that there is a group of consumers in the western world who is conscious about the environment and its relationship with consumption. Since insects are an environmentally friendly way of producing and consuming proteins, it could be a suitable alternative for animal sourced proteins (Govorushko, 2019). This relates to what House (2016) states in its research; he states that many researches show that new products are mainly accepted and used in a small group of consumers, *the innovators*, before spreading towards the major part of consumers. This was the case with sugar, tea and sushi many years ago (House, 2016).

Product form

Currently, the literature shows three ways of consuming insects by people: as a whole insect; processed into a whole insect paste; or a certain part of the insect, like the oils or

the protein meal (Govorushko, 2019). Consuming the whole insect is mainly done in countries where entomophagy is normal. Other forms, like a whole insect paste, protein meal or oil are mainly applied in the western culture where eating insects is not normal for consumers.

Multiple consumer experiments have been conducted and all of them showed that the consumer acceptance towards food containing insects is low, but that it rises, when the insects are not, or limitedly visible (Gmuer, Nuessli Guth, Hartmann & Siegrist, 2016; House, 2016; Tan et al., 2015). The insect supplements can be used as a supplement in multiple kitchens. For example, in typical food, like bread (House, 2016; Van Huis, 2013). A recent experiment by Delicatio, Schouteten, Dewettinck, Gellynck and Tzompa-Soza (2020), showed that BSF oil can replace 25% of butter in bakery products without changing the look, feel and taste of the products. Researchers even concluded that BSF oil can substitute 50% of butter in waffles without changing any sensory aspects.

Product market applications
In South America, Africa and Asia insects are consumed regularly, in rough form, not applied in a product (Van Huis, 2018). In the western world the current product assortment containing insects is very limited (Van Huis, 2018). The first insect product in the western world, a mealworm burger, has been sold in the Netherlands from 2014. In the United States a famous fast food chain was the first to introduce cricket milkshakes in 2015. Also, supermarkets in some European countries are selling insect snacks at this moment. Their assortment includes products like a protein bar including buffalo worms and crickets (Collins, Vaskou & Kountouris, 2019). Currently, no literature or internet sources can be found on current food applications specifically on the BSF in the western world.

There can be concluded that insects, especially the BSF, are a good protein source for consumers. Nevertheless, consumer acceptance of insects in food products is relatively low at this moment. This results in the fact that currently no BSF products are applied on the consumer food market. However, research shows that consumer acceptance rises when visibility decreases. In regard to the visibility, research showed that it is possible to apply the BSF in a processed form into multiple product applications.

4.2 Livestock feed market

Although it is not allowed to feed livestock with insect proteins in most countries in the western world, this paragraph shows the future possibilities for including whole BSF meal or BSF protein meal into livestock feed. First it explores the regulation regarding insect protein in livestock feed and secondly it shows research results regarding protein and whole BSF meal for poultry and pigs.

TSE regulation
Currently, it is not allowed in the EU and US to use insect protein, including proteins of the BSF in livestock feed due to the *Transmissible Spongiform Encephalopathies* (TSE) regulation (TSEregulation (EC) 999/2001) regulation (EU) 2017/893; Shelomi, 2020). This regulation prohibits the use of insect protein for livestock feed like poultry and pigs in the European Union. This is caused by the risk of illnesses like *Bovine spongiform encephalopathy* (BSE), this is commonly known as mad cow disease. This disease was caused by the occurrence of pathogenic animal protein in livestock feed, which caused a big scandal in the 1980-1990s (Finke, Rojo, Roos, Van Huis & Yen, 2015). However, according to research, this pathogenic protein has nothing to do with proteins of the BSF (Finke et al., 2015; Shelomi, 2020). Research of Finke et al., (2015) showed that the pathogenic proteins are not able to replicate in insects and are therefore not present in insects when fed on organic waste streams excluding animal or human waste.

BSF (protein) meal in poultry and pig diets
Three researches stand out regarding protein or whole BSF meal to replace soybean meal for poultry. The first research by Mwaniki, Shoveller, Huber & Kiarie (2020), showed

positive signs in completely replacing soybean meal for laying hens with defatted protein meal of the black soldier fly.
The second recent research by Pieterse, Erasmus, Uushona & Hoffman (2019), showed that whole BSF meal can be used as protein source for broiler chickens without affecting the meat quality.
However, the third research showed that completely replacing soybean meal with whole BSF meal, in diets of laying hens, caused lower digestibility. According to the authors, this can be caused by the availability of chitin in whole BSF meal (Cutrignelli et al., 2017)
Besides poultry, research also shows some positive aspects in the performance of weaning and growing pigs by replacing soybean meal with BSF protein (Spranghers et al., 2018). Yu et al. (2019), confirmed that it also has a positive effect on finishing pigs, when including 4% BSF protein meal in the diets of the finishing pigs, the carcasses and meat quality improve.

From here it can be concluded that there are possibilities regarding the replacement of soybean meal in diets of laying hens and weaning and growing pigs with BSF protein meal. For laying hens whole BSF meal is less suitable due to the chitin content. Besides, it can also be concluded that whole BSF meal can be applied into diets of broiler chickens without affecting the meat quality. The research does not show any signs of decreased digestibility, which is the case by laying hens. Nevertheless, TSE regulation still does not allow to apply BSF meal or protein meal into the diets of livestock in the majority of western countries. In the future, if legislation changes, whole BSF meal or protein meal could be applied into the market of livestock feed.

4.3 Other future applications

Literature showed positive signs regarding the application of the marketable products of the BSF in medicines and cosmetics. This paragraph will give a review of the literature regarding applications of marketable BSF products in medicine and cosmetics.

Medicine
The BSF contains antimicrobial peptides, which can be valuable in medicine (Choi et al., 2012). Due to the current problems related to resistance to antibiotics, a new antimicrobial medicine for human and livestock is needed. The ability of insects has been approved by multiple researches which show the antimicrobial aspects of various insects and its ability to be a cure to various infections and even cancer (Choi et al., 2012).
Besides antimicrobial peptides, BSF also contains chitin. Chitin is a polysaccharide with almost similar values compared to cellulose. One of the characteristics of chitin is, that it is immunological effects and that it has positive effect on lung diseases like asthma (Lee, Da Silva, Lee, Hartl & Elias, 2008; Van Huis, 2018).

Cosmetics
Currently palm oil and coconut oil are often used in cosmetics (Dubois, Breton, Linder, Fanni & Parmentier, 2007). These products became relatively expensive and palm oil is, due to its high environmental foodprint, not sustainable (Benzertiha et al., 2019; Verheyen et al., 2018). Three researches conclude that the oil part of the BSF has a fatty acid profile which is comparable to that of coconut oil (Dayrit, 2015; Rabani, Cheatsazan & Davani , 2019; Ushakova et al., 2016; Dubois et al., 2007). Furthermore, Dubois et al. (2007), claims that BSF oil, is also comparable to palm oil. Since these oils are currently used in cosmetics, BSF oil could be applied as a replacement in those products (Dubois et al., 2007; Verheyen et al., 2018).

Researches show promising results regarding the application of the antimicrobial peptides of BSF to be applied as antimicrobial medicine or chitin as support to lung diseases. It also shows positive signs regarding the application of BSF oil as a replacer for palm and coconut oil in cosmetics in the future. However, literature available is limited and more research is needed in order to be able to put a product on the market.

4.4 Conclusion

The literature review of this chapter is conducted in order to answer sub research question 3, "*What are the future product market applications of the marketable ingredients of the black soldier fly?*". There can be concluded that research shows positive results for various product applications of the BSF on four markets. However, these product market applications are currently not on available on the market.

First, literature claims that the BSF is able to perform as a sustainable (protein) source processed into various food products for consumers. By way of contrast, consumer acceptance is low at this moment. However, consumer acceptance rises when visibility of the product decreases.
Second, literature showed that the BSF protein meal is a very suitable product to replace soybean meal in the diets of laying hens and weaning, growing and finishing pigs. The supplementation of BSF in the diets of finishing pigs even improved the quality of the meat and carcasses. Additionally, whole BSF meal is suitable to replace soybean meal into the diets of broiler chickens. However, due to regulation, it is not possible to put these products on the western livestock feed market at this moment.
Third, literature claims that the antimicrobial peptides, one of the by-products of the BSF, is a suitable new antimicrobial medicine for animal and human. Besides, chitin, another by-product of the BSF, has immunological effects on lung diseases of human, and can apply into medicine.
Fourth, the oil of the BSF has similar characteristics compared to palm and coconut oil. These products are commonly used in cosmetics. Literature showed that the oil of the BSF can be applied to replace palm and coconut oil in cosmetics in the future.

There can be concluded that literature shows positive results for future market applications of the BSF. However, consumer acceptance needs to rise, regulation needs to change, and additional research is needed.

5. Key drivers for the future

This chapter will answer sub research question 4, "*What are the key drivers for the future of the current and future product market applications of the black soldier fly?",* by a PESTEL analysis. The PESTEL analysis is an analysis which assesses the macro factors which have an influence on the business environment, it also helps to predict future situations and identify key drivers for change (Yüksel, 2012). In this research, the analysis has been made on the EU industry, since most information was available on this market. This chapter will show an analysis of the future impact of political, economical, social, technological, environmental and legal influences on the industry of BSF, followed by an analysis of the influences of the PESTEL factors on the current and future product market applications. The chapter will be closed by a conclusion which will identify key drivers for the future of the current and future product market applications of the BSF.

5.1 PESTEL analysis

Political

Politics includes the political situation in the EU and its influence on the industry. Currently 27 of 51 are members of the European Union. The overall current political situation in the EU is stable (European Union, 2020). Politics also includes NGO's which can have an influence on the industry. The NGO with an influence on current agricultural companies are animal welfare organizations (Ingenbleek, Binnekamp, Van Trijp & De Vlieger, 2004). There is a possibility that these will claim the fact that insect rearing is not good for animal welfare. In a lot of countries there is a law claiming the protection of farm animals, however, due to the fact that insects are invertebrates, insects are not a part of this law (Boppré & Vane-Wright, 2019). As a result of this, there are no guidelines regarding insect welfare and killing. There is a possibility that laws regarding welfare of insects is going to change due to lobbying of NGO's (Lenaerts, Meersman, Verheyen & Van Miert, 2019).

Economical

The economy has an effect on the market of the insect industry. Research shows positive signs regarding the possibilities of the BSF, not only in processing organic waste, but also the sales of all marketable ingredients of the BSF. However, the current market volumes worldwide are much lower compared to the market chances (Hilkens & De Klerk). Currently this is shown by the market of aquafeed. According to personal communication with the aqua expert at Protix B.V., demand is much higher compared to supply at this moment. If other markets will open or other markets will expand, demand will get bigger.

Limited information is available in literature about willingness to pay of B2B in the industry. However, according to experts at Protix, willingness to pay depends per target market. According to a sales expert at Protix, willingness to pay for farmers, who are production driven is related to the price of the substitute product, in this case soybean meal. Currently, the price of BSF protein meal is nine times the price of soybean meal (Pinotti, Giromini, Ottoboni, Tretola & Marchis, 2019). This causes a need for a decrease in price for the market to expand in the future.

About willingness to pay for B2C, one article has been published about the willingness to pay by Italian consumers for substituting regular products with products containing insects. This research showed that consumers have the same to slightly lower willingness to pay for the products containing insects compared to the traditional products. However, the article also showed that willingness to pay rose when information about benefits of insects was provided on the packaging (Lombardi, Vecchio, Borrello, Caracciolo & Cembalo, 2019).

Social

Social elements of the macro environment of an industry could have an influence on the demand of a market. Consumer acceptance plays a big role in this aspect (House, 2016; Lenaerts, 2019). As described in paragraph 4.1 "*consumer food market"*, multiple

researches have shown that insects meet all the nutrient profile and protein requirements suitable for human consumption (Rumpold & Schlüter, 2013; Tao & Li, 2018; Van Huis et al, 2013). Researches also show that it is suitable to partially or totally replace multiple product ingredients in various western kitchens, without having a negative effect on taste (House, 2016; Van Huis, 2013; Delicato et al., 2020). However, consumer acceptance among insects as or in a food or non-food product is relatively low, this is mainly caused by the "disgust" factor insects have among consumers (House, 2016).

Two researches have been conducted regarding the consumer acceptance of animals fed with insects. The first experiment among Italian consumers showed that the majority of the consumers have a positive attitude towards farmed fish fed with insect meal (Mancuso, Baldi & Gasco, 2016). The second experiment was conducted among farmers, stakeholders and citizens in Belgium. This research showed that two thirds of 415 participants had a positive attitude towards the use of insects in animal feed (Verbeke et al., 2015). The positive attitude mainly regarded fish and poultry fed with insects.

Technological
New discoveries and technology developments have an influence on the industry in the future. Currently, the BSF rearing industry is very labour intensive, and there are not a lot of automatization technologies available (Van Huis, 2020). There are some patents that have been filed regarding the automatization processes of insect rearing. Regarding for example lighting and sieving insects and residue (Govorushko, 2019; Van Huis, 2020). However, these automatization technologies are relatively easy and therefore easy to copy. Due to this, most companies worldwide are very uncommunicative about the automatization technologies in their companies, since it is easy to copy by competitors. Due to this, it is unknown what the current automatization stage in the industry is. However, the European Union awards subsidies to companies to innovate, so there are technological developments under construction at this moment (IPIFF, n.d.)

Environmental
The environment has an influence on the current and future industry. Environmental change is putting pressure on the current global food system, which is according to research, one of je major drivers of environmental burdens (Van Huis et al., 2013; Van Huis, 2019). However, according to FAO, global demand for food and feed is rising (Van Huis et al., 2013). These developments cause a global growth in demand for sustainable proteins and other high value ingredients for both humans as animals. The BSF is a more sustainable alternative for traditional proteins. The BSF is able to grow on waste streams, is not land based, has relatively low GHG emission and requires limited water (Müller et al., 2018; Rumpold & Schlüter, 2013). Since environmental change is putting pressure on the current system, it opens its system for new, sustainable products (Van Huis et al., 2013).

Legal
Legal variables include regulatory aspects that affect the industry. Currently, it is not allowed to feed livestock with insect protein in the EU due to TSE regulation (TSEregulation (EC) 999/2001) regulation (EU) 2017/893). However, due to positive research results, it is possible that it will be allowed to feed pigs and poultry with insect protein in the future (Hilkens & De Klerk, 2016; Lähteenmäki-Uutela et al., 2017). International Platform of Insects for Food and Feed (IPIFF), claims that they expect that the regulation regarding insect proteins in livestock feed is going to change in 2020 (Hilkens & De Klerk, 2016).

5.2 Influence on product market applications

All the PEST factors do have an influence on the industry and its current and future product market applications. This sub paragraph will discuss the influences of the factors of the PESTEL analysis on each of the current and future product market applications. First it will discuss the influences of the PESTEL analysis on the industry as a whole including the current markets. Secondly it will discuss the key drivers for change for the future markets.

From the economical factor in the PESTEL analysis there can be concluded that current market prices of BSF products are high compared with the substitute products. However, the technological factor showed that there are technological developments and that there are subsidies awarded. Technological development will stimulate automatization practices which can make the industry less labour intensive. If the industry will become less labour intensive and companies are able to scale up, production volumes can rise, and prices may decrease. This has a positive effect on all current and future product market applications since both B2B as B2C customers are willing to pay among the substitute price.
Besides, if production volumes rise, also by-product volumes will rise. This will have a positive impact on the current product market applications regarding fertilizer and the future market applications regarding medicines. There can be concluded that technological innovation is one of the key drivers for the further expanding of the current BSF products on all future and current markets. Another factor that needs to be kept in mind for the overall industry are the political influences. NGO's could lobby for legislation about animal welfare, this is something to keep in mind.

Future markets need changes in order to become real markets. From the PESTEL analysis three key drivers for change can be identified. First, in order to open the livestock feed market for BSF protein meal, legislation needs to change. This is one of the key drivers for the future of protein meal on the livestock feed market to become a real product market application in the future.
Second, in order to apply consumer food products containing BSF on the market, consumer acceptance needs to rise. Increased consumer acceptance is one of the key drivers for the BSF to become a product on the consumer food market.
Third, in order to apply products of the BSF into products on the medicines and cosmetics market, additional research is needed. Research is not part of the PESTEL analysis. However, scientific research could have positive effects on future product market applications of the black soldier fly in the medicines and cosmetics market (De Silva & Vance, 2017). Positive research results will stimulate players on the market to include those ingredients in their products.

5.3 Conclusion

The review in this chapter is conducted in order to answer sub research question 4, "*What are the key drivers for the future of the current and future product market applications of the black soldier fly?".* From the PESTEL analysis there can be concluded that one of the most important aspects for the general future industry is that production volumes will rise, and prices will decrease. Technological innovation is one of the key drivers which can have an influence on those aspects. Automatization may lower the labour insensitivity and cause an increase in production. It is possible that this will have an influence on the prices. Technological innovation will help the industry to further expand the current BSF products on all future and current markets. However, political influences on the industry need to be kept in mind, to respond on possible influences of NGO's.

Another aspect that can be concluded is the influence of the factors on future markets. Those markets need changes in order to become real markets. In the first place, legislation needs to change in order to open the livestock market for BSF protein meal. In the second place, consumer acceptance needs to rise. And in the third place, additional research is needed in order to stimulate the use of BSF products in the medicines and cosmetics markets.

Conclusion and discussion

This chapter will provide answers to the central research question by a conclusion. Besides, in the discussion these results will be discussed. The discussion will also provide recommendations for further research and some limitations of the research.

Conclusion

This research is conducted to be able to answer the following research question: "What are the current and future product market applications of the black soldier fly larvae?". To be able to answer this research question, a combination of systematic and non-systematic literature review has been conducted.

According to the literature there can be concluded that the BSF is an insect with lots of potential, it is fast growing and able to convert low value organic waste into high value marketable ingredients. The marketable ingredients of the BSF are; meal of the whole BSF, protein meal, an oil fraction and various by-products. These marketable ingredients can be applied into products on various markets. The products mainly apply as a replacer for traditional, less sustainable products. However, not all of these product market applications are currently applied onto these markets. The literature reviewed in this research shows positive results in ten markets regarding the applications of products containing the BSF.

Currently, the BSF is applied in products and sold onto five markets.
First, the BSF is successfully applied as whole BSF meal into the diets of at least four fish species and shrimps. The products are applied to totally or partially replace fish meal or soybean meal without having negative effects.
Second, BSF products are applied in three product variants on the livestock feed market.

- First, BSF oil as a feed product is sold on the poultry market replacing soybean oil. Research showed no negative effects on poultry and one of the researches even showed positive effects on the cholesterol and fat level of the chickens.
- Second, BSF oil is also successfully applied as a feed product to nursery pigs, partially replacing soybean oil. This application showed improved growth among the pigs.
- Third, Live BSF larvae are sold as a supplement to partially replace soybean meal into the diets of laying hens. Literature showed that this application had positive effects on pecking behavior among hens.

Third, whole BSF meal is applied into products on the pet food market. Traditionally BSF are sold alive to reptiles and amphibians. However, a more recent successful product market application is the application of whole BSF meal into cats' and dog's food. It is used as a replacer for traditional proteins in pet food, which compete with human and other animal food resources.
Fourth, the rearing by-products of the BSF, could successfully be applied onto the market of fertilizers as a natural fertilizer to replace chemical fertilizer.
Fifth, BSF oil is currently applied as an ingredient for biodiesel generation, as a replacer for vegetable oil. One of the positive aspects of BSF oil over vegetable oil, is that it does not compete with human food resources and agricultural land.

These product market applications are currently sold on the market. However, on all of those markets, market shares of these products are low compared to traditional products on the markets. Besides, compared to substitute products, the prices of BSF products are high.

Besides the current products the literature shows promising results regarding the application of BSF on 4 other markets. However, in contrast to the previously discussed product market applications, these product market applications do not exist yet.
First, the BSF can be applied into consumer food products. Literature shows that the BSF is a very suitable product for consumers, since it contains high value proteins. The BSF is

applicable in various forms into food products: as a whole insect, processed into paste, as whole BSF meal, or as oil or protein meal. Those product forms can be applied into various products in multiple markets. Despite the fact that research shows that the BSF is a very suitable protein source for consumers, consumer acceptance of food products containing insects is low. Nevertheless, literature shows that consumer acceptance rises when visibility of the insect decreases.
Second, BSF protein meal can be applied onto the livestock feed market. Literature shows positive results for the partly or total replacement of soybean meal by BSF protein in the diets of laying hens and weaning, growing and finishing pigs. However, due to TSE regulation it is not allowed at this moment to feed livestock with protein powder.
Third, antimicrobial peptides, one of the by-products of the BSF, can be applied on the medicines market. According to literature, new antimicrobial medicines are needed due to current problems related to antibiotics resistance.
Fourth, BSF oil can be applied onto the cosmetics market. According to literature, it has same characteristics compared to coconut and palm oil, which are often used product in cosmetics. However, these products are expensive and less sustainable. BSF oil could be used to replace those products in cosmetics.

There can be concluded that research shows positive outcomes for current and future product market applications of the BSF in various markets. However, at this moment, market volumes of current product applications are very small, and prices are high compared with substitute products. It is important that production volumes will rise. Technological development is able to stimulate automatization in the industry, automatization can make the industry less labour intensive and allows companies to scale up. This may rise production volumes and decrease prices. There can be concluded that technological development is one if the key drivers for the future industry. Besides, change in legislation, rising consumer acceptance and additional research is needed in order to open future markets.

Discussion

In the discussion, the research results and the limitations of this research will be discussed. Besides it will provide some recommendations for further research.

Research results

Research results have shown that the BSF is an insect with high quality marketable ingredients that can be supplied in various products on multiple markets. It is already been applied in some markets; however, the market volumes are very small. This is probably caused by the fact that there are not a lot of (big) producing companies worldwide and the fact that BSF is not a very well-known product supplement in various markets. It can also be caused by the fact that prices of BSF products are higher compared to substitute products. Despite the fact that current market volumes are small, all target markets, have a positive compound annual growth rate. This is a positive aspect of those markets, and there is a possibility that this will open these markets for the BSF products. However, in order to open and expand markets, production volumes need to rise. According to the PESTEL analysis, technological development is able to stimulate automatization which will allow companies to become labour intensive, scale up and lowers prices. However, at this moment it is unknown what the stage of technological development in the industry is, since companies are very uncommunicative about. Besides, results show that it is important for markets to open, for example the consumer food market. However, consumer acceptance is relatively low, this can be caused by the fact that consumers are unfamiliar with insects as a consumption product. Besides consumers are unknown with the advantages of consuming insects. It is important to educate consumers in order to reach a higher level of consumer acceptance.

Limitations

This research show six limitations, in this part, the limitations will be discussed.

First, since the industry is a young industry, and has low production volumes, it was relatively difficult to provide an estimation of market shares of BSF products in the various markets. Since no market volume numbers were available, the estimations have been made together with the market experts of Protix. Besides the fact that these persons are market experts and that they have a lot of knowledge in this field, it makes these estimations less reliable than when a peer reviewed source would have been consulted.
Second, total market volumes of markets in which the products were applied are based on free samples of market reports by market research agencies. This makes these results less reliable than when a peer reviewed source would have been consulted.
Third, the knowledge gap of this research, the overview of current product-market applications, has been analyzed by Scopus. However, Scopus is a database containing mainly scientific articles. Due to this, there is only a small chance that management practice related articles would be found in this database. Nevertheless, during this research the knowledge gap has remained since no overview article has been found in other databases or the internet.
Fourth limitation of this study is that it is mainly based on literature. Conducting a research only by using secondary data by literature review involves some limitations. Not all relevant literature was accessible by Wageningen University. However, this has been resolved by the R&D department of Protix B.V., since they had access to most of this information.
Fifth limitation of this research is the fact that the snowballing method which has been used, may give a biased view since this method often gives the same kind of articles. This limitation has been rejected by the fact that the key articles on which the snowballing is applied are gathered from different databases and authors.
Sixth limitation is that some product market applications were based on one or two studies only. This is caused by the fact that no more literature about those subjects was available.

Future research
The sixth limitation shows that for some product market applications, limited literature was available. Therefore, future quantitative research is recommended regarding the application of BSF on the pig feed, pet food, medicines, cosmetics and fertilizers markets. Positive research results could create awareness among players in those markets and create market openings for BSF products. Also, additional quantitative research could be conducted regarding the effects of insect protein meal on livestock. Positive research results could stimulate legislation to change and the market to open. Besides, additional quantitative or qualitative research is needed regarding consumer acceptance of BSF products aimed at the consumer food market. Consumer acceptance needs to rise in order to apply those products on the market.

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Appendices

Appendix 1 | PRISMA Diagram

This diagram gives a description about how many documents were found by the pre-research using Scopus, how many were excluded and on which criterion the exclusion was based.

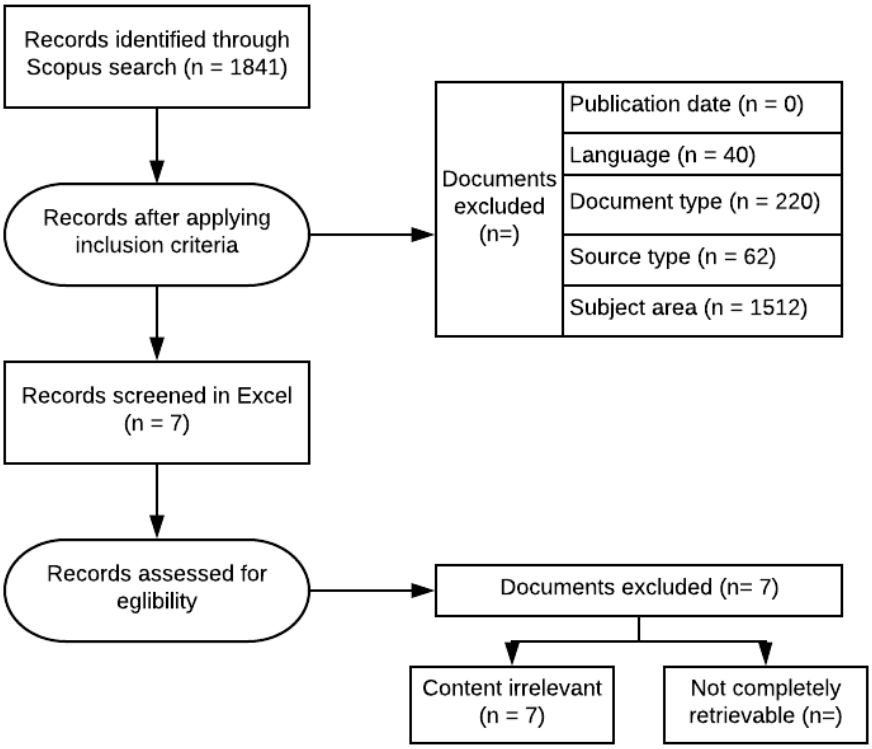

Figure 3. PRISMA-diagram search query knowledge gap

Appendix 2 | TRL Levels

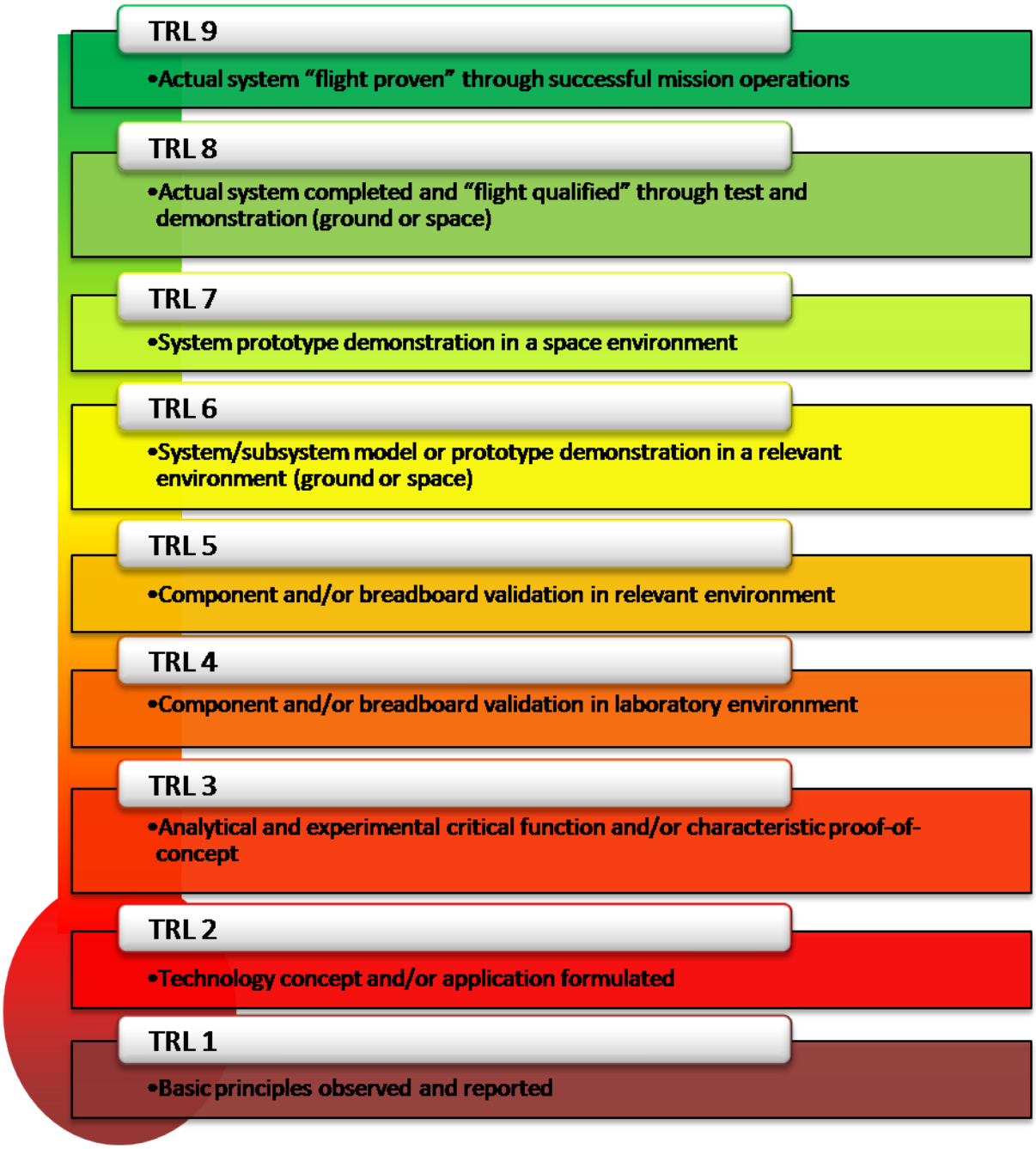

Figure 4. Technology Readiness Levels (TRL) (NASA, 2012)

Appendix 3 | PRISMA Diagram

Appendix 3.1 PRISMA Diagram research question 1

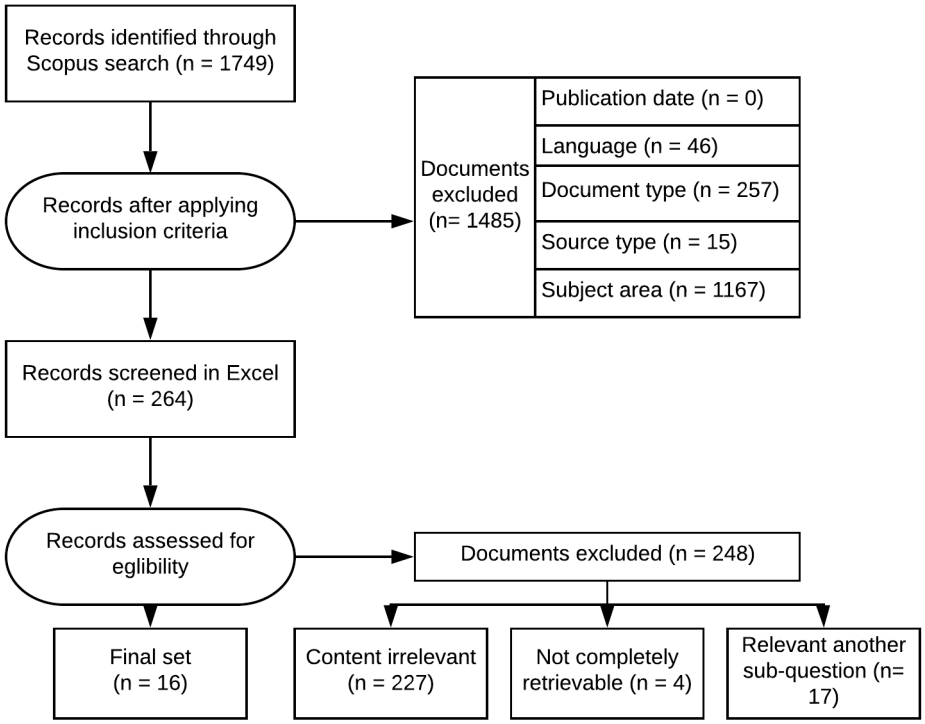

Figure 5. PRISMA-diagram search query sub research question 1

Appendix 3.2 PRISMA Diagram research question 2

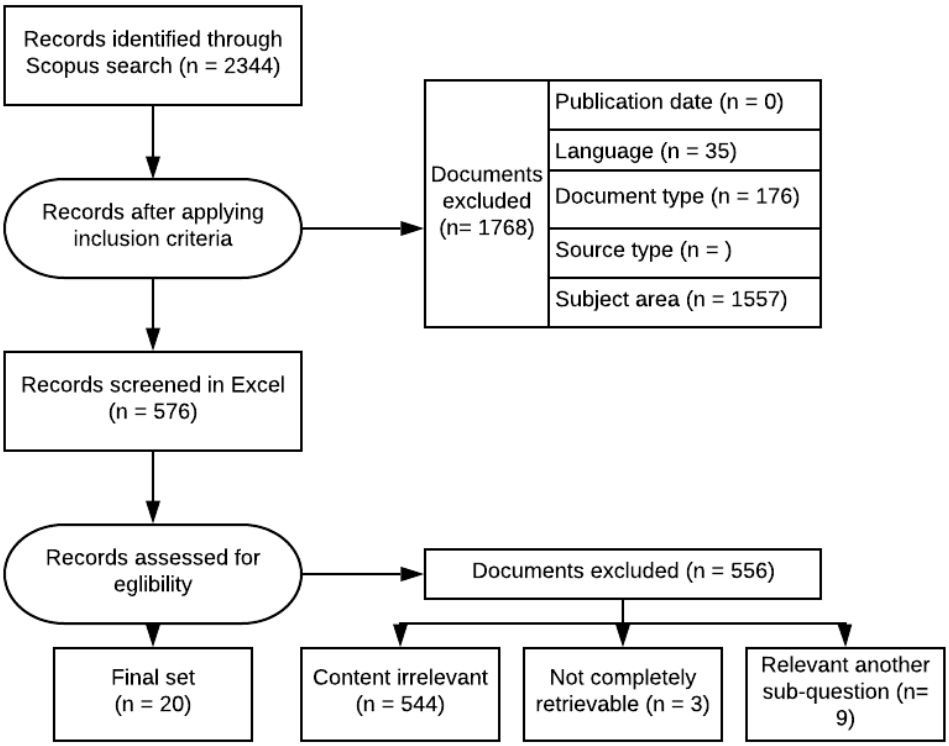

Figure 6. PRISMA-diagram search query sub research question 2

Appendix 3.3 PRISMA Diagram research question 3

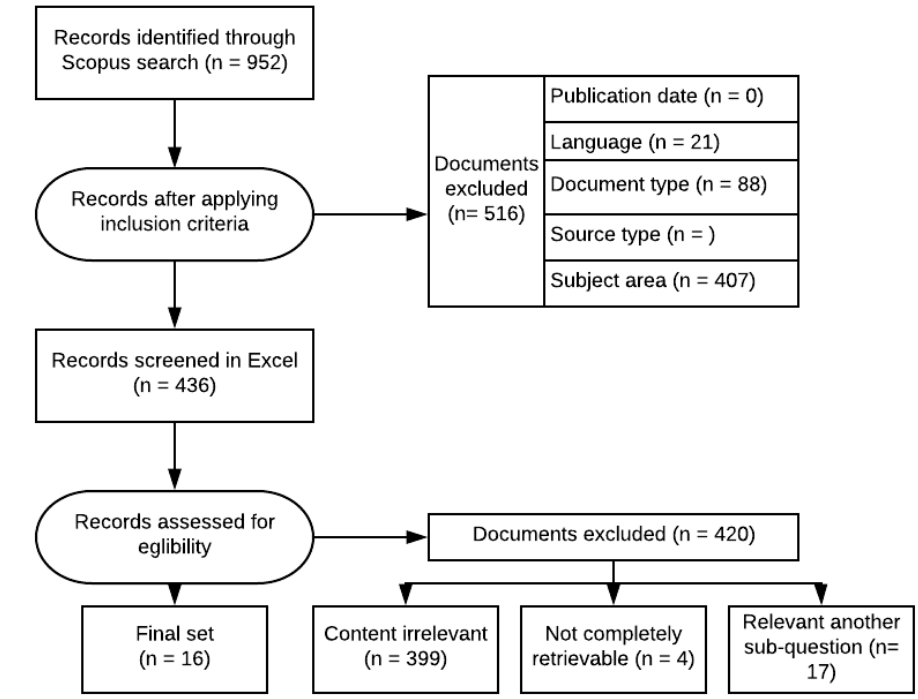

Figure 7. PRISMA-diagram search query sub research question 3

Appendix 3.4 PRISMA Diagram research question 4

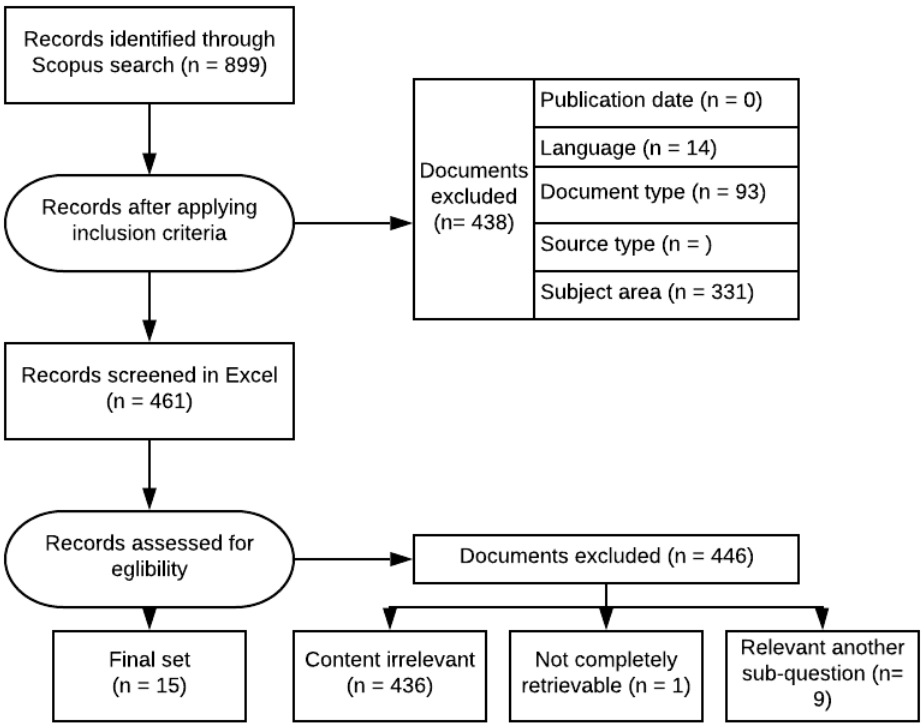

Figure 8. PRISMA-diagram search query sub research question 4