Master Thesis

FUTURE TECHNOLOGIES IN ORGANIC WASTE MANAGEMENT IN DENMARK, CZECH REPUBLIC, AND SE ASIA

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Abstract

With a growing population in the world, overall food consumption is also growing. If no new technologies are developed in the food sector, it could have some severe consequences such as poverty, hunger, a decrease in human health, climate change, depletion of water resources, and land degradation. One of the new technologies, which is still studied, is the substitution of plant protein with insect protein in animal feeding. Insects are feeding on manure, food waste, or abattoir waste. There have already been several trials, which were very successful. The insects have a lower impact on the environment than protein-based plant cultivation.

One of the insects which are rich in protein and fat is called Black Soldier Fly. This study is based on the knowledge and reviews of the BSF larvae, which reduce the biowaste as their source of feed. The rearing of BSF larvae is still under development and studies. However, it has a tremendous potential to produce protein-based larvae meal, which can substitute the protein-based plants in animal feed. The rearing of BSFL has one significant advantage, which is the reduction of biowaste. The biowaste is the largest part of the MSW, especially in low and middle-low income countries which makes a significant impact on the environment. The new technology of rearing the BSFL would increase the reduction in organic waste management and also the production of protein-based and oil-based products.

There have been proposed two systems, one for the BSF treatment facility in Denmark and the Czech Republic, the other for the BSF treatment facility in Indonesia and Vietnam. The proposed systems are compared in protein production, oil production, and waste processing. The protein production is based on the comparison between the BSF treatment facility in Denmark and the Czech Republic, facility in Indonesia and Vietnam, and soybean production. The oil production is based on the comparison between the BSFL oil in Denmark and the Czech Republic, the BSFL oil in Indonesia and Vietnam, rapeseed oil, palm oil, and soybean oil. Finally, the waste processing is based on the comparison between the residue composting at the BSF treatment facility, incineration process, composting, and biogas production.

The comparison of protein production, oil production, and waste processing is assessed when using the ReCiPe methodology. The ReCiPe methodology defines two sets of impact categories, midpoint, and endpoint. The impact assessment is performed with the software openLCA.

The results from the impact assessment showed that the BSF treatment facility is the best solution at the production of protein-based substitution in animal feed, especially in Denmark and the Czech

Republic. The BSF treatment facility in Indonesia and Vietnam must improve their waste management by sorting biowaste and use household organic waste to feed BSF larvae and produce protein and oil-based substitution.

However, the results from oil production also showed that BSFL oil is a better choice compared to other oils. Thus, the compensation of BSL oil for other oil can be provided in each country.

Finally, the residue composting at the BSF treatment facility has the lowest impact on the environment. Thus, it is better to use food waste from households in the BSF treatment facility than in biogas production, which has a significant impact on the environment.

List of Abbreviations

3R – Reuse, Recycle, Reduce

5-DOLL – Abbreviation for Five-Day-Old-Larvae

BSF – Black Soldier fly, *Hermetia illucens*

BSFL – Black soldier fly larvae

CH_4 – Methane

CO_2 – Carbon dioxide

EU – European countries

FU – Functional unit

GHG – The greenhouse gas

GWP – Global Warming Potential

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

MSW – Municipal Solid Waste

N_2O – Nitrous oxide

ReCiPe – A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level

SDG – Sustainable Development Goals

SE – Southeast

List of Figures

List of Tables

List of Equation

Table of Contents

1. Introduction

During the time of Napoleon, there were less than 1 billion people on Earth. Since World War II, it has been statistically proven that the population is growing a billion people every 12-15 years (Population matters 1991). However, today there is more than double the population than back in 1970, and this number will increase. It is assumed that the population will grow to 10 billion people in 2050. Therefore, with the increasing population, the consumption of food will also increase. That means that it is necessary to find new alternatives and new technologies to feed humanity. More food means more resources needed, but that can be a problem in the future, so there should be more focus on food waste and by-products of food.

Urban solid waste management is currently one of the most severe environmental problems not only in low- and middle-income countries but in the whole world, due to the rapid urbanization and growth in urban population. Due to more pressing environmental concerns and the growing population, there must be a new system of dealing with municipal waste, which is more sustainable and has the concept of a circular economy (Dortmans B.M.A. 2017).

Waste management is essential for the food industry and the well-being of humanity. The food industry generates a massive amount of waste and by-products all over the world. Recycling biowaste is a limited process, especially in low- and middle-income countries, although it is the most significant part of all the generated municipal waste (Dortmans B.M.A. 2017). Nevertheless, biowaste or by-products are a unique source of bio-active, nutraceuticals, and many beneficial components. Biowaste, or by-products, are converted by insect larvae using the example of Black Soldier Fly (BSF), *Hermetia illucens*.

As was already mentioned, proper waste management is essential for human well-being, and it also relates to the Sustainable Development Goals. SDGs are also known as the Global Goals, and their primary purpose is eradicating poverty, protecting the planet, and living in peace and prosperity.

From all the 17 SDGs, only 6 of them are mainly related to the challenge of using insects as feed for animals, number 1 (No poverty), 2 (Zero hunger), 3 (Good health and well-being), 13 (Climate action), 14 (Life below water), 15 (Life on land), via Figure **1** (United Nations Development Programme 2016).

Figure 1: Sustainable Development Goals

The world's appetite for meat is a growing issue. Higher meat consumption means more feed for farm animals. It is not only humans who need meat, but also our pets need meat. Production of animal food is increasing pressure on the land and the water resources. That is why we need to develop new technology for feeding animals and humans. Every animal needs protein to be healthy and have enough muscles for a normal healthy life. Insects can provide as much protein as animals could. Harvested BSF larvae are a new promising opportunity for animal feed as a source of protein. Insects have a lower environmental cost, and they can be fed on manure or other types of organic waste, such as offal, leftover food, and grains discarded by breweries (Kupferschmidt 2015).

1.1 Aim of the study

This study aims to develop a sustainable and profitable concept of feed production from insects, using selected residue and waste streams from the food industry. This study is based on a comparison of protein sources in animal feed.

This study will also assess under which circumstances (i.e., background system conditions) implementation of protein production from organic waste using the Black Soldier Fly technology makes sense from the environmental point of view.

The study will contain a comparison between Denmark, the Czech Republic, Indonesia, and Vietnam. The comparison will include the energy production, waste management, environmental sectors, and food production of these countries. Furthermore, the study will focus on insect-based protein vs. plant-based protein for animal feed. If it is possible to use insect-based food as a substitute, it will decrease the impact on the Earth and environment, due to that BSF treatment facilities would not take the same amount of land as the production of plant-based food would.

The result of this research is expected to show that insect-based food will be a better solution for animal food than a plant-based food, based on an environmental point of view. Furthermore, it will have a positive effect on the environment and higher nutritional values for animals.

It is assumed, the implementation of this new technology will be more straightforward in SE Asia, where they already use food based on insects for animal feed and human consumption. In Denmark and the Czech Republic, the economy is better, which means many people have the capital to buy beef, chicken, or pork. Therefore, in these countries, the production of insect-based food is not a big thing. Also, there is a significant cultural difference between the four countries, what is considered human food, and what is not.

1.2 Waste management

Since ancient times there has been waste accompanied by humanity. Waste is the most common by-product of all human society. Waste is generated by construction and industrial activities, transportation, agriculture, household, and many other types of daily waste. Municipal waste and sewage sludge from wastewater treatment are visible by-products of the human population (Ministry of the Environment of the Czech Republic 2014).

Organic waste is a quantitatively significant group of waste in municipal waste. Each waste has a specific treatment method, which has positive and negative effects on the environment. Biowaste composes approximately 40-50 % of the total amount of municipal waste produced (Třídění odpadu 2020). Most of the biowaste is used for its plant nutrients and organic substances, which can be used in a natural cycle as an organic fertilizer (compost). Biowaste can be treated in many ways; one type of treatment is the anaerobic digestion technology. During this treatment, it generates another product, so-called biogas. Biogas can be used in transportation as fuel or at the production of electricity and heat (Ministry of the Environment of the Czech Republic 2014).

It is essential to separate biowaste from municipal solid waste during collections. This is an excellent way to avoid difficulties during the process of making biowaste into energy or materials. This method is not a new process in countries where waste management is on a reasonable level, but there are still countries where the waste management is not high. In some developing countries, waste management is on a low level, where waste is not collected correctly and placed in landfills, which are usually not even sanitized and cultivated. If biowaste is placed in landfills, there is a high potential for leakage of methane and leachate, which can have a massive impact on the environment.

The waste regulations in each country set the basic rules for waste treatment. Each country has their own goals and targets for waste treatment methods. The optimum way of achieving these goals are set out in waste management plans by the waste regulations (Ministry of the Environment of the Czech Republic 2014).

Countries of low and middle-income, face tremendous challenges with providing sufficient solid waste management services to guarantee public health and avoid pollution of the environment (Adeline Mertenat 2018) (Helkar P. B. 2016).

1.2.1 Denmark

Denmark is officially named the Kingdom of Denmark; it is a Nordic country in Northern Europe and one of the Scandinavian countries. Denmark has a border with Germany. The population of Denmark is approximately 5,8 million inhabitants. Denmark has a total area of 42.943 km^2, and approximately 61 % of this is agricultural land (Statistic Denmark 2020).

Denmark is very aware of waste, due to the economic activity in society. The stronger the economy, the more waste is produced. Denmark had to come a long way to manage its waste management responsibly. However, Denmark is still one of the largest producers of waste per capita in Europe. In 2011, Danish households produced approximately 572 kg of waste per person per year (The Danish Government 2013).

In 2017, Denmark generated approximately 11,7 million tonnes of waste. Denmark is good at recycling due to placing recycling containers throughout the country, which is still improving and upgrading. In 2017, the recycling rate was 35 %, which was 4 million tonnes of waste recycled. The Danish Government wants to decrease incinerating and increase the recycling rate. In 2017 about half of the municipal waste was incinerated with energy recovery (OECD 2019). Municipal waste landfilling has decreased in the years 2005 and 2017, from 5 % to 1 %, mainly due to incineration with energy recovery (Miljø-og-Fødevareministeriet 2019).

The Danish Government has a goal and vision to protect the Danish resources and materials and recycle more household waste in the next few years while incinerating less (The Danish Government 2013). The landfill will be used only for materials that are uneconomical to recycle or incinerate. The Government also set a goal to increase the recycling rate to 50 % by 2022 (OECD 2019).

1.2.2 Czech Republic

The Czech Republic is placed in Central Europe bordered by Germany, Poland, Slovakia, and Austria. The population of the Czech Republic is approximately 10,65 million inhabitants. The total area is 78.866 km^2, and around 54 % is agricultural land (UNdata 2005).

The development of waste management legislation began in 1991 in the Czech Republic. Since then, Czech legislation had to adapt to meet the requirements and regulations of the European Union. In the field of waste management, the primary legal document was changed in 2014 and is Law no. 185/2001 Coll. on Waste (Soukupová 2014, 295-321).

Municipalities are the producers of the municipal waste and have responsibility for the physical waste management in their area. Every community has its system of collection, removal, and other waste management attached to the municipal regulations. Financing the waste management system is part of the municipal budgets (Ministry of the Environment of the Czech Republic 2014).

Municipal waste includes the collection of plastic, paper, metal, glass, bio-waste, and others (Rybová 2019). In 2019, Czech Republic generated approximately 38,6 million tonnes of waste annually, around 26 % was recycled, 11,8 % ended up in landfill, 0,2 % was incinerated without energy recovery, and approximately 3 % was recovered as energy (Czech Statistical Office 2020) (Eurostat 2018).

1.2.3 Indonesia

Indonesia is a country placed in Southeast Asia and Oceania, between the Pacific and Indian ocean. Indonesia consists of more than seventeen thousand islands. The population of Indonesia is approximately 267,7 million inhabitants. The total area of the land is 1,905 million km^2, and from the total area, approximately 33 % is agricultural land (Statistic Indonesia 2019).

Indonesia generates nearly 70 million tonnes of waste annually. Plastic waste is the greatest challenge in Indonesia, and approximately 14 % of waste is plastic. Waste collection is inferior in this country, approximately 81 % of waste is unsorted, and end up in landfills (The World Bank, M. B. Junerosano 2019). Unfortunately, one of the world's largest landfills, Bantargebang, is located near the capital city of Indonesia, Jakarta. Every day, approximately 7 thousand tonnes of waste end up in the Bantargebang landfill (Aziza 2019). Over 70 % of landfills are unsanitized, so the waste is leaking into the ocean, groundwater, soil, and the air, which leads to unstoppable pollution. Indonesian waste management makes it difficult to recycle and reuse waste due to the waste ending up in landfill instead of getting recycled. According to researchers, the recycling rate is approximately 2 % in this country and 7,5 % in urban regions (The World Bank, M. B. Junerosano 2019) (Damanhuri 2017).

According to the World Bank's "Indonesia – Marine debris hotspot rapid assessment," 20 % of plastic end up in coastal water and rivers. The study established that Indonesia is the second-largest contributor to plastic pollution in the oceans, after China. This is the result of severe pollution in Indonesia. Plastic waste and waste, in general, are the biggest threat to Indonesia's environment (The World Bank, M. B. Junerosano 2019).

The Government of Indonesia has set a target of reducing landfill by 20 % in 5 years. The reduction effort would consist of the 3R's (reuse, recycle, reduce), higher producer responsibility, increasing the capacity and number of recycling stations. This goal can be archived by better waste collections, waste to energy, urban farming, and composting (Secretary General of the National Energy Council 2019).

1.2.4 Vietnam

Vietnam, officially the Socialist Republic of Vietnam, is located in Southeast Asia. Vietnam is a middle-income country with a population of approximately 97,37 million inhabitants. The total area of the land is 331.212 km^2, and of the total area, approximately 37 % is agricultural land (BBC 2019) (General Statistics Office of Viet Nam 2020).

Waste, and the environmental problems associated with it, have raised the concern for the public and Vietnamese Government.

Among the many methods which can be used in waste management, landfilling is still the cheapest and most prevalent solution in Vietnam. In order to build landfills that meet the environmental conditions, the location of landfills plays a significant role. However, finding the best location for landfills is a challenging task in Vietnam (Luu Duc Cuong 2017).

Only 20 % of Vietnam's landfills are sanitized, according to the director of the Vietnam Institute for Urban Environment and Technology (Anh 2019). There are 200 incinerations in Vietnam that burn waste, but most of them can only handle 5-10 tonnes of waste per day. In Vietnam, approximately 30 million tonnes of waste are generated annually, and only 75-80 % of it is collected, which is done manually or semi-mechanically. Of the total amount of waste, only 10 %

is recovered for reusing or recycling. According to a World Bank report, Vietnam is one of the world's four most significant producers of plastic waste. The situation is critical, especially in cities, coastal areas, and riverbanks (Anh 2019) (The World Bank, T. Nguyen 2019).

Over 70 % of waste is buried in the ground, which exposes soil to loss and pollution (Anh 2019). Waste-to-energy technologies can reduce waste volume by 90 % and generate energy for the urban area. Vietnam could produce approximately 6 billion kWh in 2050 from waste. The Government has a target for the collection, recycling, and reusing of waste. By the end of the year 2020, Vietnam should be able to treat 90 % of urban solid waste (Das 2018).

1.3 Soybean production

There is a worldwide demand for soybean. Soy is a globally traded commodity, produced in both temperate and tropical climates, and serves as a source of vegetable oils and protein (WWF 2012). Soy is commonly used as an alternative to meat or dairy, and as an ingredient in vegetarian or non-vegetarian cuisine (Newman 2016). Soybean is known as a source of protein, which is useful for those who have cut out animal meat from their diet.

Approximately 70 % of the world’s soybean production is going to animal feed, 7 % of soybean are turned into human food, and the rest is used for soybean oil or biodiesel production (Jdel Carmen 2020). Soybean is not only made for food such as soy sauce, tofu, and meat substitutes, but it is also made in the form of soybean meal. Soybean is mainly used in animal feed due to its richness in protein. Soybean can be a good source of protein, but as a global commodity plant, it can leave a damaging footprint on the environment (Newman 2016).

The United States of America, Argentina, and Brazil are the biggest producers of soybean. Together they are producing around 80 % of the world's soy (WWF 2012). Soybean needs a vast water supply to grow. Approximately 9.500 liters of water is necessary to produce 1 tonne of soybean and nearly 300 liters of water to produce 1 liter of soymilk.

Production of soybean has been accused of contributing to deforestation in the Amazon rainforests. Cutting trees in the forest to plant soybean or any other crop in Amazon rainforests is a threat to the climate. Amazon's rainforests contain around 90-140 billion tonnes of carbon. That is between 9 to 14 years of current global human-generated carbon emissions (Newman 2016).

Deforestation has a tremendous effect on climate change, animals, plants, health, and the human population, so yet another good reason to find a better solution of using different sources of protein for animal feed (Food and Agriculture Organization of United Nations 2020).

1.3.1 Denmark

The global consumption of protein is significantly rising; from 2007 to 2030 will increase the consumption of protein by 70 % (Janne Hansen 2018). Annually, Danes use approximately 1,5 million tonnes of soybean for feed, most of it is mainly imported from Brazil and Argentina (Statistic Denmark 2020).

Soybean protein is usually used in animal feed, whereas Denmark does not have soybean production on their land. However, Denmark has the potential to produce enough protein for animal feed by themself. The new protein source for food and feed can be seaweed, insects, grass, fava beans, etc. High potential is in rearing insects, which are rich in protein, and would be an excellent supplement for soybean protein, especially in animal feed. Denmark can supplement its food protein demand and export it to other countries. Supplement for soybean protein will come from Danish land, industrial facilities, and aquatic environments (Janne Hansen 2018).

1.3.2 Czech Republic

Production of soybean in the Czech Republic is approximately around 25.000 to 30.000 tonnes per year (Figure 2), the current domestic production of soybean reaches approximately 27.000 tonnes annually, which is around 9 % of Czech consumption. Many countries import soybean from Argentina or Brazil, but Czech prefers import from European countries. Czech imports a large amount of soybean, the biggest exporter is Germany. In 2020, Czech is set to import 2.064 tonnes of soybean from Germany. The second-biggest exporter of soybean is Slovakia, with 568,4 tonnes of soybean. Most of the exporters are from Europe, although only a minimal amount of soybean is imported from China and Korea (Food and Agriculture Organization of United Nations 2020) (Czech Statistical Office 2020).

Figure **2** shows the oscillation between 2000 and 2018. This decrease and increase of soybean production are the main result of dry weather, or too cold days of the previous years, which resulted in a significant reduction in yields.

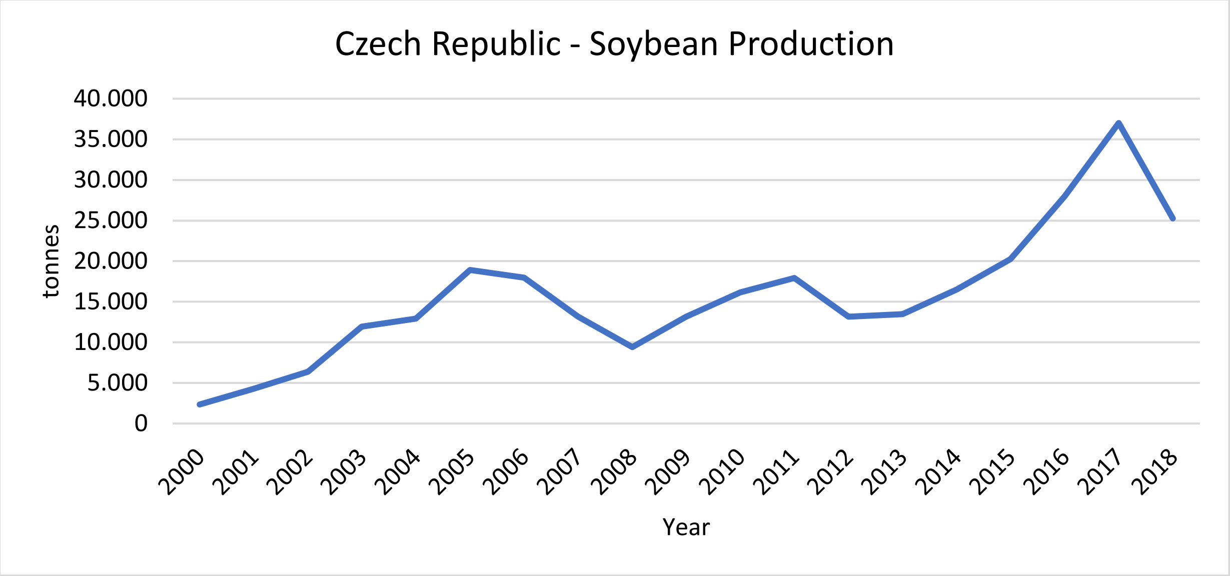


Figure 2: Soybean Production in Czech **(Food and Agriculture Organization of United Nations 2020)**

1.3.3 Indonesia

Based on Figure **3**, soybean production has been increasing and decreasing between 2000 and 2018. Finally, from 2017 the production of soybean quickly increased. Approximately 40 % of the total consumption is produced in Indonesia. The rest, approximately 60 %, is imported from other countries. The import of soybean increased by 294 % between 2000 and 2019 (Statistic Indonesia 2019). The most prominent exporter of soybean to Indonesia is the USA, and the rest is imported from Canada and Malaysia (Wang 2018).

Figure **3** shows the shortfall of soybean supply in 2002, 2007, 2011, 2013, and 2017. The capability of the domestic production, to fill the domestic market, is continuously declining. After 2000 more than 50 % of the domestic needs were met by imports, and in 2004, the imports reached 65 %. It is estimated that domestic market share will continue to grow by increasing demand for soybean (Etty Susilowati 2013).

In Indonesia, soybean production is most laborious during the dry season, in which farmers usually suffer from water shortages (William Shurtleff 2010).

Indonesia has enormous potential for substituting soybean with insects. The BSF Facility project is placed in Indonesia, and it is very successful. Insects are helping Indonesia to reduce its biowaste.

Figure 3: Soybean Production in Indonesia **(Food and Agriculture Organization of United Nations 2020)**

1.3.4 Vietnam

According to Figure **4**, it is evident that soybean production in Vietnam has been declining in recent years due to low yields. Furthermore, a continuing decline in the growing area of soybean, as farmers change to more profitable crops, including other field crops, vegetables, and fruits (Huong Nguyen, Megan Francic 2020).

Since soybean production is falling below the demand from the food industry, aquaculture feed, and livestock sectors, Vietnam has to import soybean. The leading exporter of soybean is the USA due to competitive prices (Donley 2018). Soybean imports are set to increase by up to 15 %. In the year 2018/2019, Vietnam has imported 1,9 million tonnes of soybean (Benison 2018).

Soybean has been cultivated for a very long time in Vietnam. Although, the production in Vietnam has been declining in recent years due to low yields and a continuing decline in the growing area as farmers switch to more profitable crops, including other field crops and vegetables and fruits. According to Figure **4**, the production continues to fall sharply below the demand from the food industry, the agriculture, and livestock feed sector (Huong Nguyen, Megan Francic 2020).

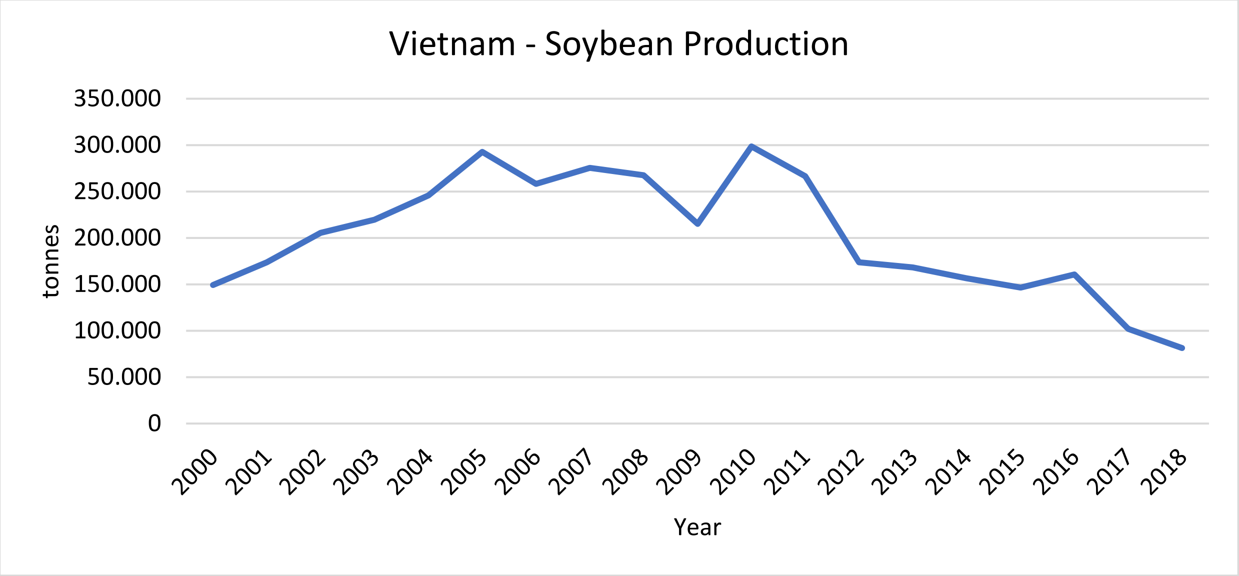


Figure 4: Soybean Production in Vietnam **(Food and Agriculture Organization of United Nations 2020)**

1.4 Livestock

1.4.1 Denmark

Denmark has adapted many ecological solutions that have made a better and more sustainable country. There is still a big challenge with food waste. Denmark is considered one of the eco-friendliest countries in the whole world. However, meat consumption and meat production are highly destructive to the environment (Tikkanen 2017). The meat industry creates methane, which is 25 times more destructive than carbon dioxide in a 20-year time frame (Vaidyanathan 2015).

Pork meat is the heart of Danish food culture without any doubts. Typical Danish dinner would be pork meat with potatoes. Unfortunately, these traditions in Danish food culture were the reason Denmark was ranked as one of the highest in ecological footprint in Living Planet Report, 2014 (McLellan September, 2014). The main reason behind those results was the Danish agriculture industry and the high meat consumption by the Danes. The Danish Council of Ethics did not ignore these negative results and therefore recommended an initial tax on beef in 2016 (Tikkanen 2017). As Figure **5** shows, Denmark’s number one rearing is poultry, while pork is in second place. Pork is highly consumed and exported to Germany, Poland, UK, Italy, Japan, and China (King 2019). In Denmark, cattle are mainly kept because of the milk, secondary for meat.

In 2017, Danes consumed 25,5 kg of beef meat per capita, 54,6 kg of pig meat per capita, and 33,6 kg of poultry meat per capita (Statistic Denmark 2020).

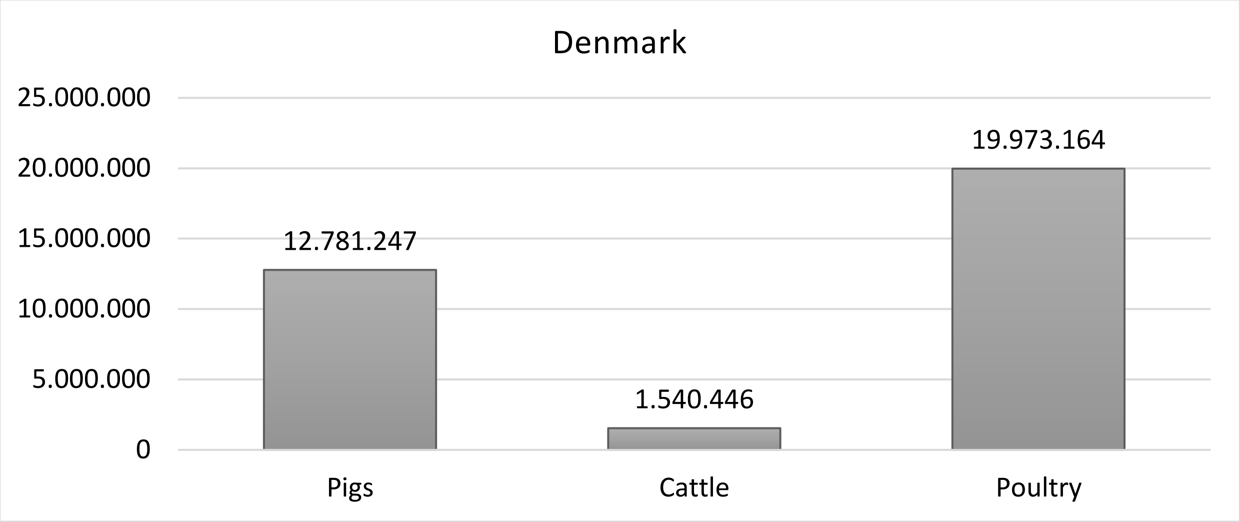


Figure 5: Animal Production in Denmark **(Statistic Denmark 2020)**

1.4.2 Czech Republic

Chicken meat is a very popular meat in the Czech Republic. The number of poultry, pigs, and cattle is shown in Figure **6** (Czech Statistical Office 2020). In 2017, Czech consumed 7,7 kg of beef meat per capita, 46,1 kg of pig meat per capita, and 20,6 kg of poultry meat per capita (Statistic Denmark 2020) (CIWF 2019).

The Czech Republic has a higher export than import of poultry meat. The export increased by about 1,6 % between the years 2019 and 2020. Czech is also exporting pork meat. In 2019 approximately 2,700 tonnes of meat were exported. The production of beef is slightly increasing; the export and import of beef are almost in balance (Doc. MVDr. J. Kamenik 2019).

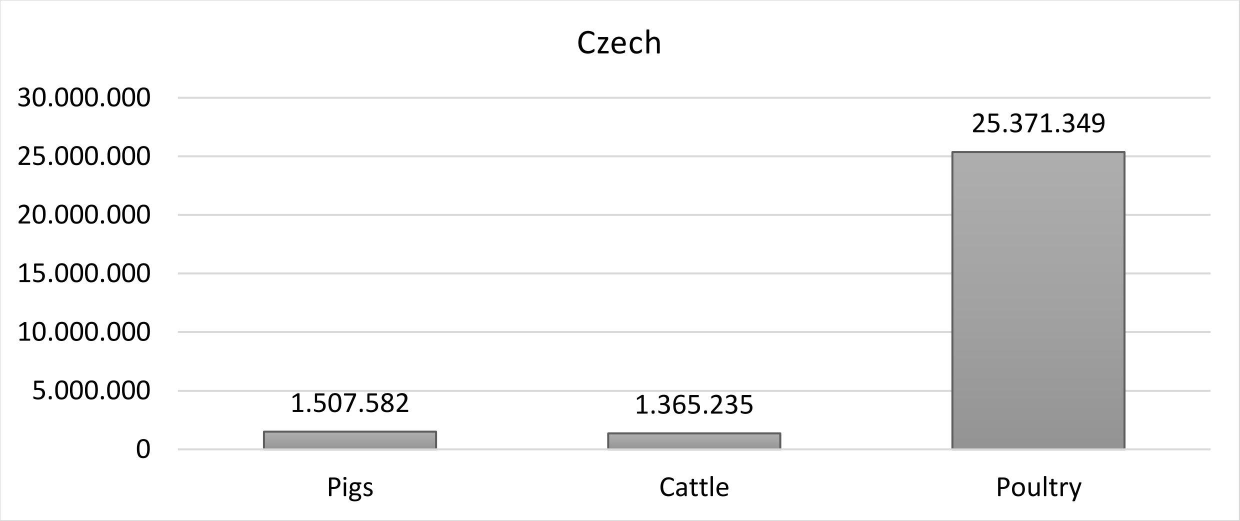


Figure 6: Animal Production in Czech **(Czech Statistical Office 2020)**

1.4.3 Indonesia

Pigs and cattle are not very popular in Indonesia because of the Indonesian religion. However, as Figure **7** shows, poultry is very wide across Indonesia. In 2018 the number of poultry was almost 3,14 billion (Statistic Indonesia 2019). The demand in the domestic market is expected to grow very fast in the next couple of years as the Indonesian population may reach 318 million inhabitants in 2045 (Euromeat 2014). It is evident that poultry breeding is very popular in Indonesia, and that is also one of the reasons insect feeding is starting to be a better solution for poultry. Indonesian poultry is easy to feed with entire BSF larvae as a substitute for soybean protein.

In 2018, Indonesian consumed 2 kg of beef meat per capita, 1 kg of pig meat per capita, and 7,6 kg of poultry meat per capita (OECD-FAO 2019).

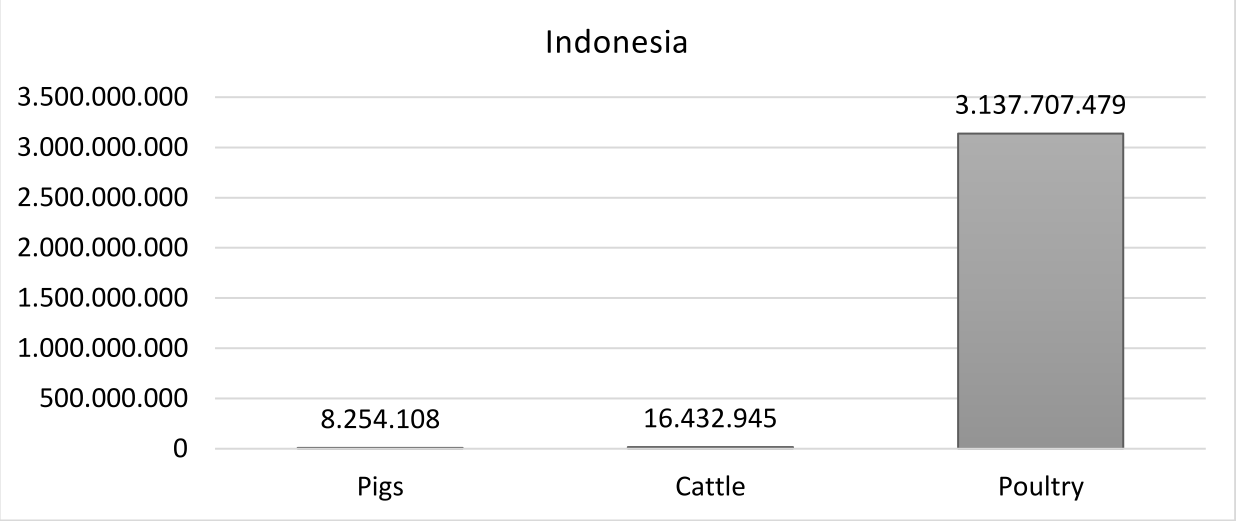


Figure 7: Animal Production in Indonesia **(Statistic Indonesia 2019)**

1.4.4 Vietnam

The Vietnamese people are starting to change their diet. Vietnamese cuisine is famous for its use of vegetables and herbs; nowadays, meat consumption in Vietnam is increasing at an astounding rate. People eat more than before, and especially they eat more meat and animal products. Vietnam is dramatically changing. Over the past three decades, this country was one of Asia's poorest countries, and its diet consisted mainly of vegetables and rice. The meat was only on extraordinary occasions. Today, it is common to have meat in every meal of the day (Hansen 2018). As Figure **8** shows, the number of poultry is tremendous compared to pigs and poultry. Poultry is very popular in Vietnamese cuisine, whether it is its meat, organs, or claws. Pigs and cattle are not very popular in Vietnam due to the Vietnamese religion.

In 2018, Vietnamese consumed 9,3 kg of beef meat per capita, 29,7 kg of pig meat per capita, and 13,4 kg of poultry meat per capita (OECD-FAO 2019).

According to the production volume of main livestock products in Vietnam, it is evident that poultry meat is on the first place with over 408 million of pieces. In 2019, poultry meat production was at the highest, followed by pigs with a volume of approximately 28 thousand of pieces, and cattle with a volume of 5,8 million pieces (Doan 2020).

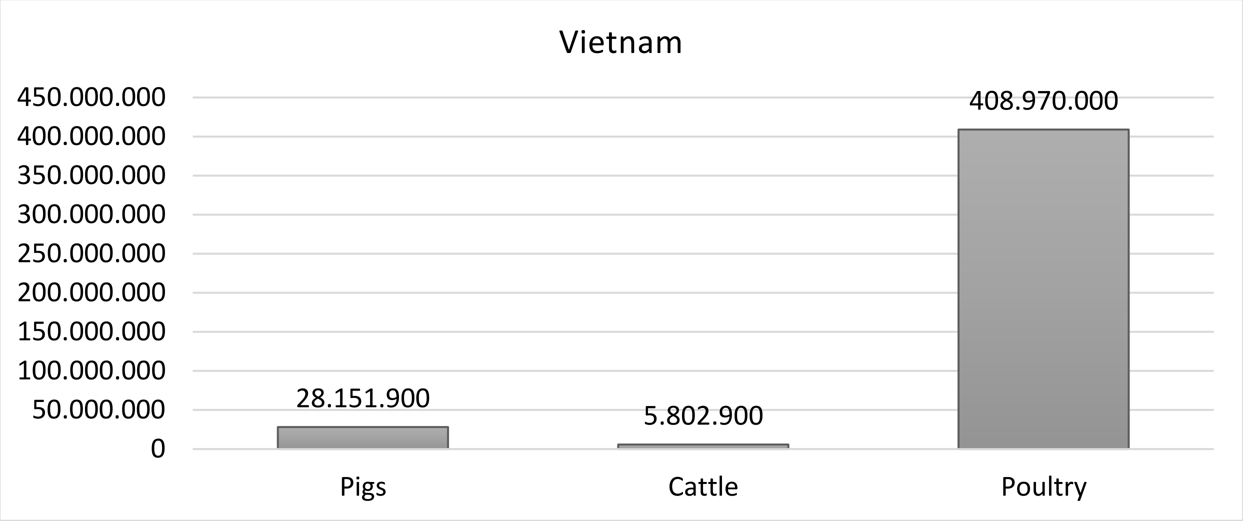


Figure 8: Animal Production in Vietnam **(General Statistics Office of Viet Nam 2020)**

1.5 Energy grid

1.5.1 Denmark

In 2018, Danish primary energy production was mainly from crude oil (42 %), renewable energy (29 %) and natural gas (26 %), Figure **9**. Denmark has set a goal to increase the recycling rate of household waste by 50 % by 2022 and to be fossil-free by 2050. To achieve that, it is required to use as much renewable energy as possible (Danish Energy Agency 2020). To complete these goals, the entire energy system and infrastructure have to change. Furthermore, the energy system must be 100 % renewable energy, which includes wind, biomass, and solar. This will reduce greenhouse gas emissions and increase the security of supply.

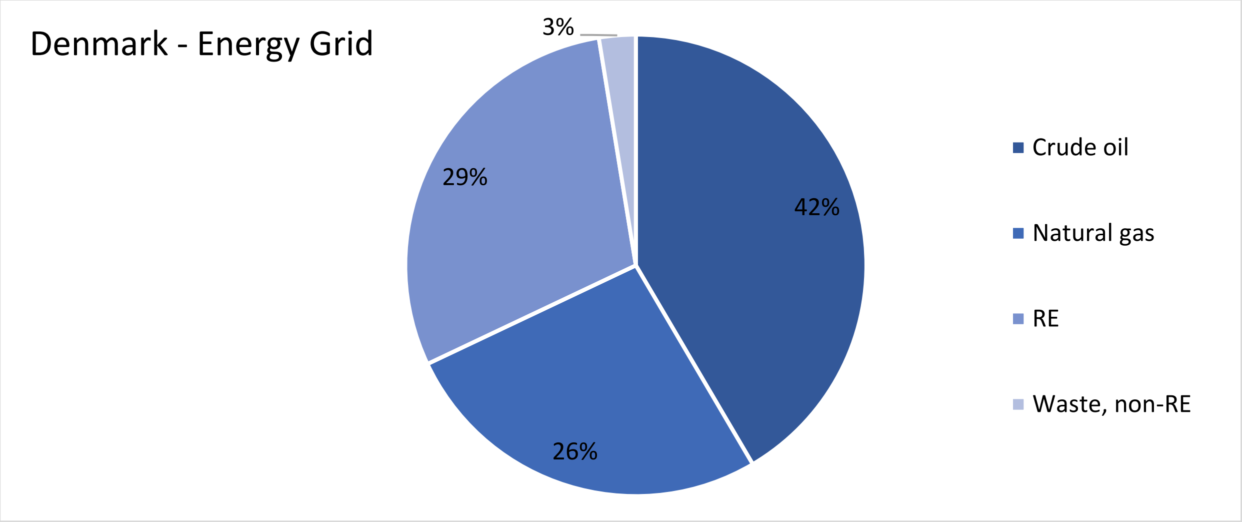


Figure 9: Danish Energy Grid **(Danish Energy Agency 2017)**

1.5.2 Czech Republic

The most significant source in producing energy is fossil fuels (35 %), petroleum and products of it (21 %) and nuclear power (17 %), Figure **10** (Energetický regulační úřad 2019). The nuclear power supply is widespread in Czech, because of its two nuclear power stations. During the lifetime and operations of those two nuclear power stations, it will generate at least 4.000 tonnes of highly radioactive waste, which must be stored somewhere. There are discussions about the many different types of storage and disposal of radioactive waste. Radioactive waste was thought to be deposited in deep layers of underground, eternally frozen soil, the sea, under the seabed, in Antarctic glaciers, or by firing it into extra-terrestrial space. Finally, nuclear waste was deposited in deep rock formations, where it should be safe for thousands to millions of years. This construction of a deep geological repository will have an impact on the environment, and it will change the landscape (Jaderné Elektrárny 2016).

There are a new vision and goal by increasing renewable energy to 20,8% and decreasing GHG emissions by 2030. Another essential target for 2030 is decreasing the percentage of coal power plants in the energy grid share, which is the most significant source of GHG emissions. Currently, almost 50 % of electricity production is produced by coal in the Czech Republic (Jan Boček 2019).

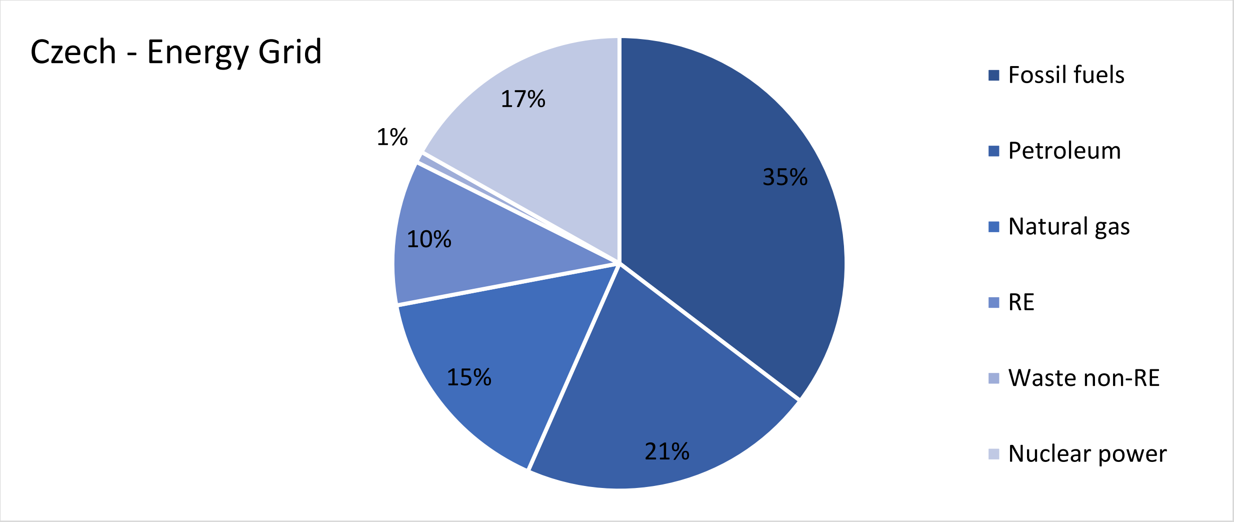


Figure 10: Czech Energy Grid **(Energetický regulační úřad 2019)**

1.5.3 Indonesia

The primary energy production in Indonesia consists of coal (50 %), gas (29 %), renewable energy (14 %), and oil (7 %), Figure **11** (Secretary General of the National Energy Council 2019). Approximately 64 % of total production (LNG and coal) was exported in 2018. Besides that, Indonesia imports energy, especially petroleum products and crude oil, and a small volume of high-ranking coal for necessary needs in the industrial sector. Renewable energy consists of hydro, geothermal, bioenergy, solar energy, wind, and ocean energy. In Indonesia, the National Energy Policy aims to produce at least 23 % renewable energy by 2025 by minimizing the use of oil at least by 25 % by 2025 (Suharyati 2019).

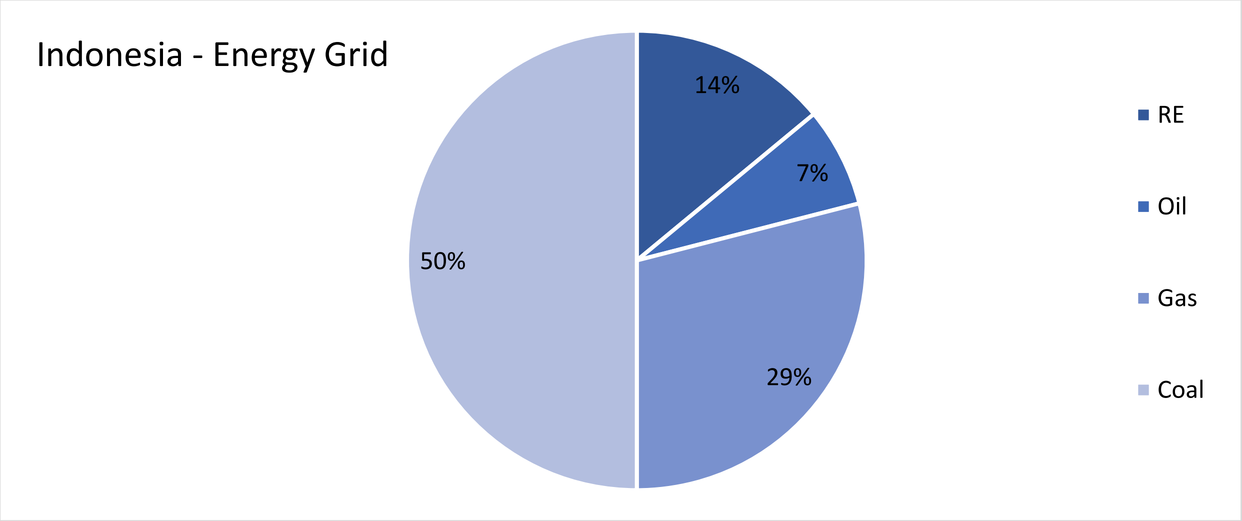


Figure 11: Indonesian Energy Grid **(Suharyati 2019)**

1.5.4 Vietnam

The primary energy production in Vietnam consists of coal (36 %), crude oil (25 %), and renewable energy (29 %), Figure **12** (Ministry of Industry and Trade in Vietnam 2019) (IEA 2020).

The goal of energy efficiency is to reduce energy consumption by 1 % per year to promote energy savings in all sectors. Other goals in the National Energy Policy have been taken into consideration. Energy demand optimizes fossil energy and domestic gas consumption priority for the national industry raw material (Suharyati 2019).

In the past few decades, Vietnam has been one of the most productive and fast-growing economies of the region and worldwide. Economic growth has led to improved quality of life and decreased poverty rate in Vietnam. Economic growth is still a very high priority for the Government. However, political goals and vision emphasize that fast development must go side by side with sustainable development (Danish Energy Agency 2017).

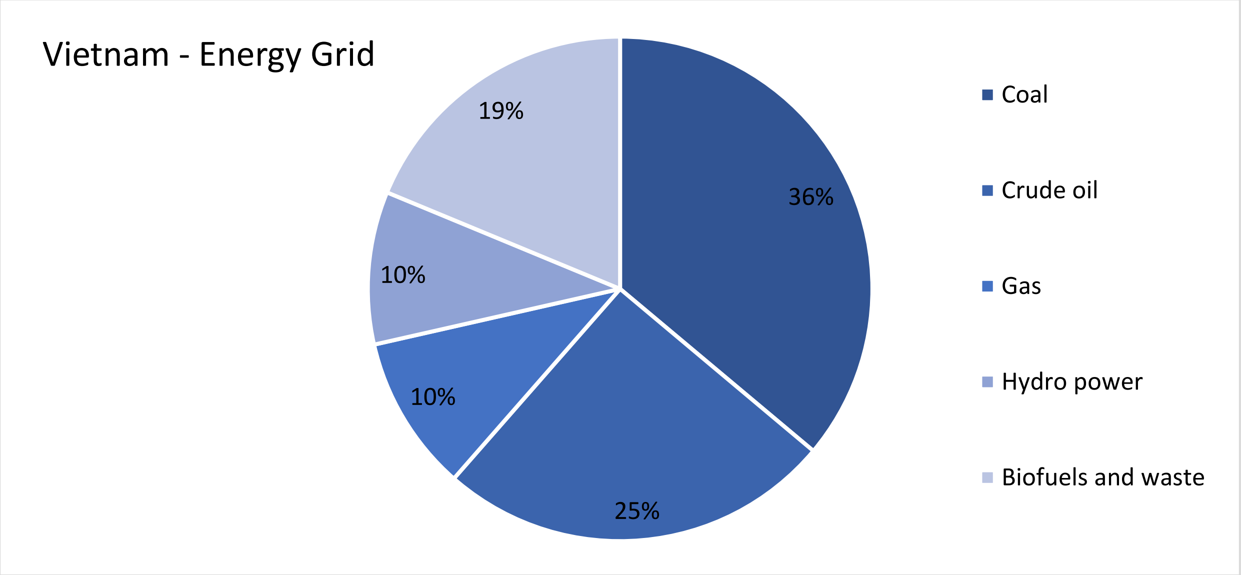


Figure 12: Vietnamese Energy Grid **(Ministry of Industry and Trade 2019) (IEA 2020)**

The energy sector also plays a massive role in promoting sustainable economic development (Ministry of Industry and Trade in Vietnam 2019). The proportion of energy consumption will be growing, especially in the industrial and construction sector (Danish Energy Agency 2017). The wind power should have 2.000 MW capacity installed, and solar power should have 4.000 MW capacity installed by 2030. Vietnam currently uses 42 % of renewable energy for the electricity grid (Ministry of Industry and Trade 2019). The target percentage of renewable energy in primary energy is 32 % by 2030. Another target is decreasing GHG emissions by 20-30 % by 2030 and final energy saving by 8-10 % (Ministry of Industry and Trade in Vietnam 2019).

1.6 BSF Facility

Segregated biowaste is used for feeding BSF larvae, which have been bred in a nursery. The BSF larvae eat and reduce the waste mass. At the end of the process, BSF larvae are harvested and used raw for feeding animals. This step depends on the geographical placement of the facility. If customers are nearby, it is easier to sell them alive without further processing. If the placement of the facility is not perfect, and larvae need to be used as a product that needs to be transported and stored, then there has to be a further process. The process consists of drying, crushing, and palletizing larvae. After the sieving process, the waste residue can potentially be used as a soil amendment with fertilizing properties (Dortmans B.M.A. 2017).

Introduction to BSF Processing Facility

In this chapter, there will be a more thorough description of every step of the BSF processing facility, as Figure **13** shows. The BSF larvae are rich in protein and oil, so they are an excellent source in animal feed.

The BSF treatment facility is divided into five main processing units, which are:

- BSF rearing unit
- Waste pre-processing and receiving unit
- BSF treatment unit
- BSF larvae harvesting unit
- Post-treatment unit (residue processing, larvae refining)

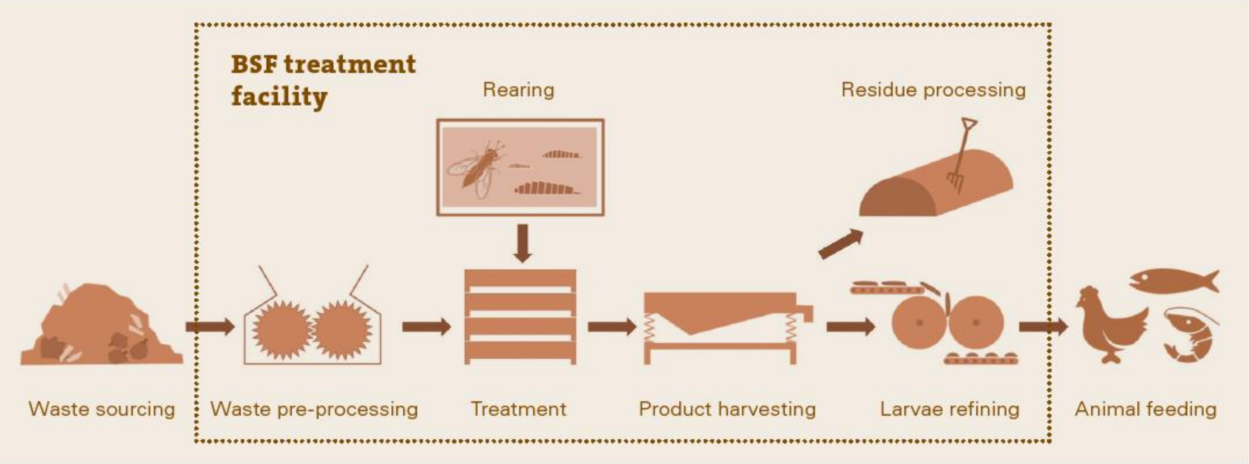


Figure 13: BSF treatment facility **(Dortmans B.M.A. 2017)**

This facility, as was already mentioned, depends on many factors in each country. Differences in each facility can vary due to climate conditions such as humidity and temperature, or economic situation, respective capital, and operating costs of the facility.

Further, larvae can be used as a raw product, or protein meal in pellets or powder, or as a larval oil. The waste residue can be used as a soil amendment or for biogas production (Dortmans B.M.A. 2017).

Black Soldier fly

This Section will be focusing on a detailed description and understanding why BSF is a very suitable insect for organic waste management and which benefits there is using it. The benefits are high efficiency of waste reduction and further use for soil amendment or biogas production (Dortmans B.M.A. 2017).

The black soldier fly (BSF), *Hermetia illucens*, inhabit the whole world, excluding Antarctica. The BSF naturally occurs most in the tropical, subtropical, and warm temperate zones between the latitudes of 40°S and 45°N, as described in Figure **14**.

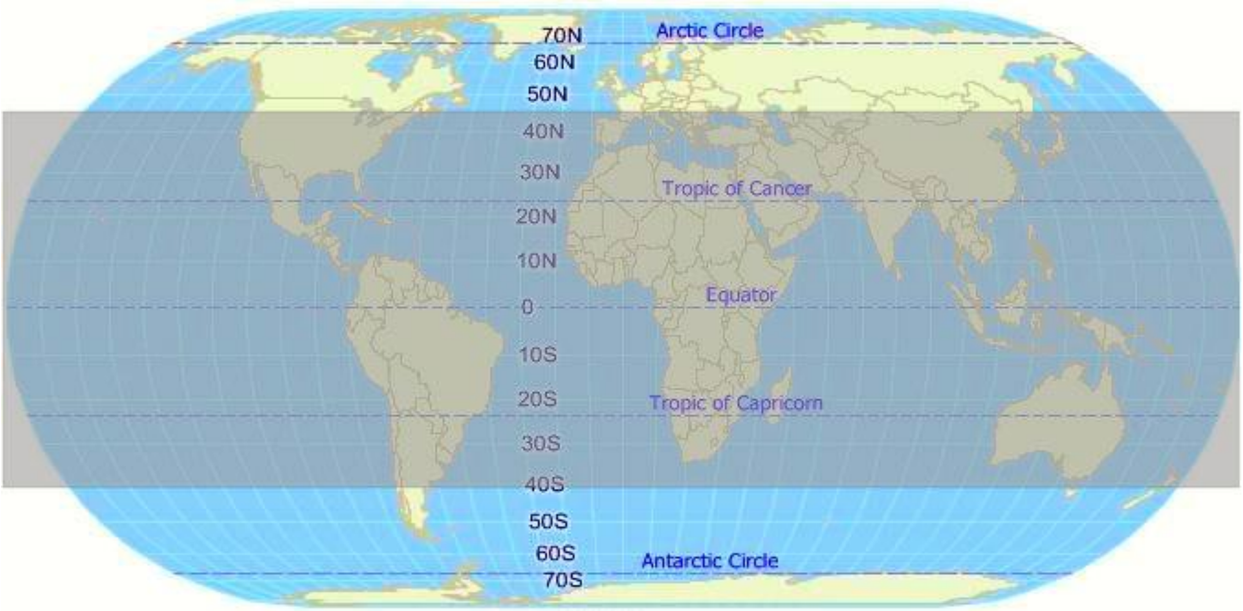


Figure 14: Distributed area of Black Soldier Fly

These saprophagous species rely on environments where it is possible to find decomposing matter where larvae can grow and feed. The use of these larvae is excellent in organic waste management for their macronutrient quality, especially proteins and lipids. There have been many types of research where it is speculated that the number of mating varied according to the season and differences in the intensity of sunlight, which is caused by the change of seasons (Hoc B 2019).

The female fly lays between 400 and 800 eggs, very close to the decomposing matter, into dry and small sheltered cavities. The reason why females fly lay her eggs close to the decomposing organic matter is that it will ensure that after hatching, larvae will have their first food source very close. The sheltered cavities are protecting unhatched eggs from predators and dehydration by direct sunlight. After approximately four days, the eggs start to hatch, and emerging larvae are only a few millimeters big. After hatch, these emerged larvae will start to search for food and start to feed themselves on decomposing organic matter, which is nearby. The growth of the larvae will take approximately 14 to 16 days, and from a few millimeters, they can grow into a size around 2,5 centimeters length and 0,5 centimeters width. The BSF life stages are shown in Figure **15** below the text (Dortmans B.M.A. 2017).

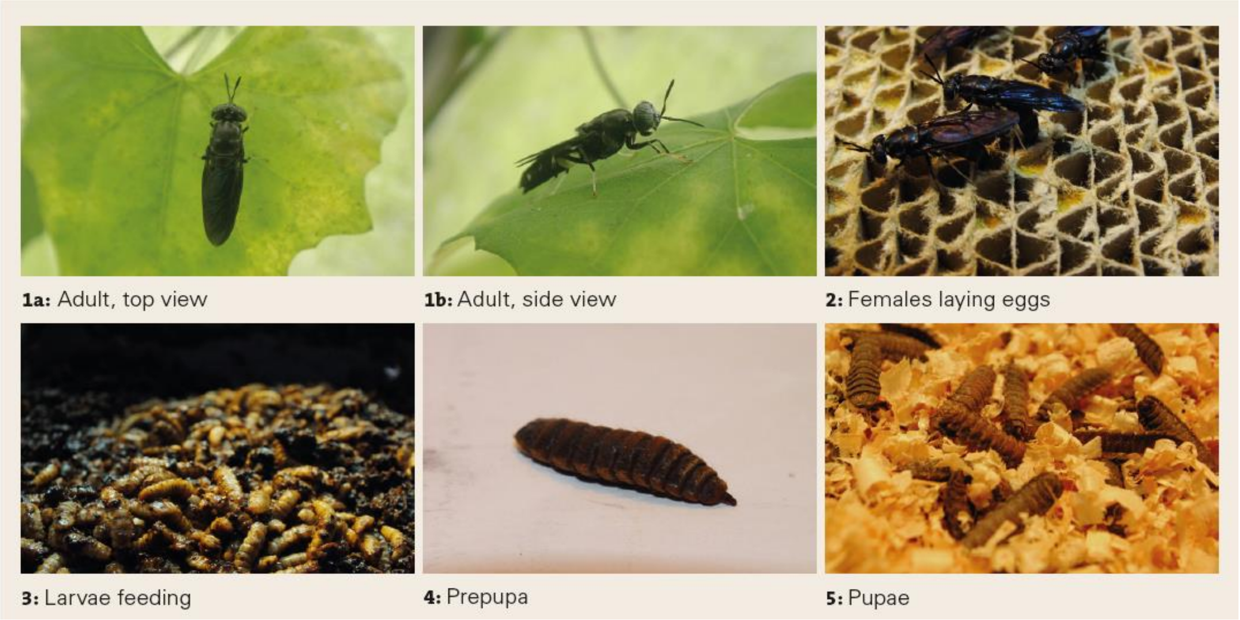


Figure 15: Life stages of the Black Soldier Fly, Photos: Nandayure Studt Solano (1a, 1b), Samuel Blyth (2, 3, 4), Sandec (5)

The BSF larva is a very resistant organism that can extend its life cycle under unfavorable conditions. The only feeding stage for the larvae is when the larvae are trying to get enough stored protein and fat so that they can develop from larvae into flies. After emerging as flies, they will start to find mates, copulate with them, and females will lay eggs before they die (Dortmans B.M.A. 2017).

After all five larval stages, as shown in Figure **15**, the larvae reach the last and final larval stage, called prepupa. Larvae change their color into dark brown to charcoal grey. During transformation on prepupa, larvae replace its mouthpart with a hook-shaped structure. This hook is used for more effortless movement from a food source or to a dry place that should be nearby. This place is vital for protection against direct sunlight, predators, and temperature, and it is where the imago emerges from the pupa phase and can fly off (Dortmans B.M.A. 2017).

The flies live only one week after their emergence. During their short life, they will search for a partner, copulate, and females will lay eggs. During their short life, flies do not need food but only water to stay hydrated. Due to science research, it is known that BSF prefers to copulate in the light of the morning. That is why BSF facilities should contain "love cages" with light to attract their attention and give them a signal to copulate after they have been in the dark cages. The perfect temperature of the environment should be between 25 - 32°C. Humid weather may prolonge their lifespan and give higher chances for successful reproduction (Dortmans B.M.A. 2017).

Optimal environmental conditions for rearing BSF larvae can be summarized as:

- **Environment**: larvae do not like direct sunlight; they prefer a slightly shaded environment with a perfect temperature between 25 and 32°C. If the food is in direct light, larvae will crawl away from light and move deeper into the layer of the food. In the case of warmer temperatures, larvae will move to more shaded places. If there is too cold weather, larvae's metabolism will slow down, and they will eat less and develop slower also (Dortmans B.M.A. 2017).
- **Required nutrients of the food**: for good larvae growth, substrates should be rich in protein and easily available carbohydrates. Ongoing research shows that larvae might easily consume biowaste if it has been through some bacterial process or fungal decomposition process. Larvae do not have chewing mouthparts, so water content in the food has to be between 70 % and 90 %, so ingesting the substance will be easier for larvae (Dortmans B.M.A. 2017).

1.6.1 BSF Rearing Unit

The BSF rearing unit has to ensure that the treatment of a defined amount of biowaste will be archived by providing a defined number of five-day-old larvae called 5-DOLL. It is essential to control every production step and monitor the performance of each step during the rearing. For proper controlling of the number of larvae, it is essential to build a well-engineered nursery. This nursery helps to estimate how many flies will emerge from eggs, how many eggs packages will be deposited, how many larvae will hatch from eggs, and how many larvae will be available for biowaste treatment. Monitoring the survival rates and deaths in this cycle helps to avoid problems and help to predict the number of larvae. Data are provided based on a rearing unit, as Figure 16 shows (Dortmans B.M.A. 2017).

Egg harvesting

From an organization perspective, it is essential to keep all egg packages in one place, making it easier to harvest eggs. The egg packages, so-called eggies, are placed in the love cages where female flies can lay eggs. To attract female flies, and make them lay their eggs into eggies, there is an "attractant" which mimics decomposing organic matter. Female flies lay their eggs close to decomposing organic matter because it will ensure that after hatching, larvae will have their first food source very close. Eggies with eggs packages are harvested before any larvae hatch (Dortmans B.M.A. 2017).

Eggies can be in many different shapes and materials, as Figure **16** shows. It is vital to keep in mind that every touch or move of the egg packages or eggs, will decrease the change of the survival rate of the eggs. It is possible to minimize egg handling by weighing the whole package of eggs and the weight of the eggies. Figure **17** describes three different material options, on the first picture from the left is eggie, which is usually used in ponds and aquariums as filter media. In the middle is a stack of wooden sheets with a small gap between them created by pins, the last one from right is a cardboard honeycomb (Dortmans B.M.A. 2017).

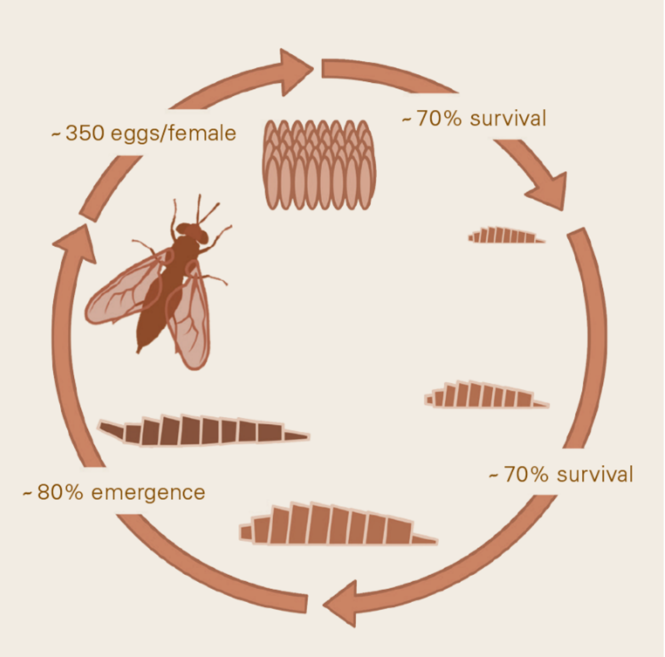


Figure 16: Performance indicators of a BSF rearing facility **(Dortmans B.M.A. 2017)**

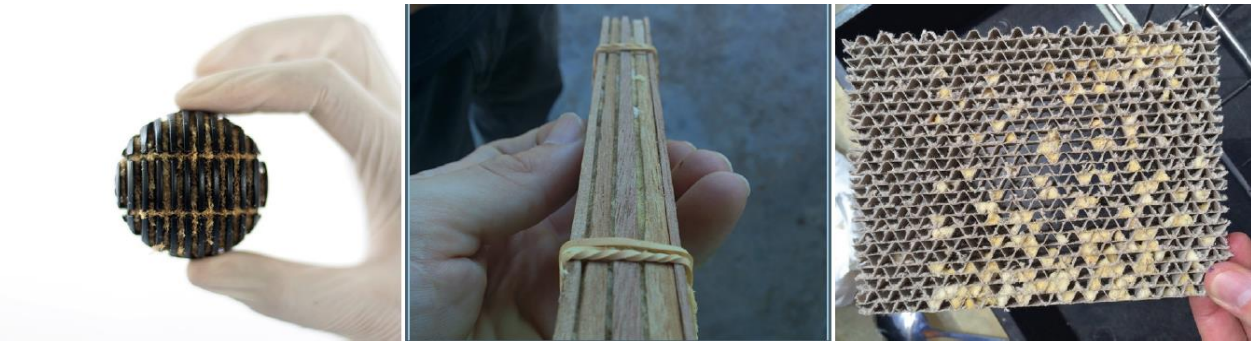


Figure 17: Different shapes and materials of eggies **(Dortmans B.M.A. 2017)**

It is necessary to design eggies as light as possible and to have the same weight; thus, it will be easier to weigh and calculate the respective egg weight. Some of the materials for eggies, respectively wood, and cardboard may absorb surrounding moisture and change the total weight of the eggies over time. Material such as plastic can prevent this error, but choosing reusable eggie, which can be cleaned easily, is a better solution for the environment. There is also a possibility to use a disposable one-use eggie (Dortmans B.M.A. 2017).

Weighting eggies is simple. During the egg harvesting, the weight of eggs is the difference between empty and full eggies (Dortmans B.M.A. 2017).

Egg hatching

The harvested eggies are placed into a hatching container where there is a food source placed under the eggies. All eggies, even if they are not from the same day, are placed into the same hatching container. Each eggie has a different color of string around them, as Figure 18 shows. It will then be obvious which eggie is from which day. After a couple of days, larvae will fall into the container with the food source. A starter with a high-quality food source, chicken feed mixed with water, is used for the freshly hatched larvae. The food has to contain 70 % of water, which will make it easier for consumption (Dortmans B.M.A. 2017).

Figure 18: Hatching container with harvested eggies and high-quality food source **(Dortmans B.M.A. 2017)**

However, the easiest way to use them in waste management is when larvae are the same age and size, which allows to plan when waste input is necessary. For the best efficiency rate, it is important to monitor when the larvae are hatched from eggs, their age, size, and numbers. Larvae are fed for five days in the same hatching container. After five days, 5-DOL is replaced into a new container where there already is biowaste, here they will be fed for approximately another twelve days (Dortmans B.M.A. 2017).

It is hard work to count each larva. However, it can be estimated by counting only a few of the larvae, as a small sample around 2 g, then it is extrapolated based on the total weight of all 5-DOL. Only a small number of the 5-DOL is kept for further mating in the rearing unit. This, of course, depends on the amount of the waste, number of hatched larvae and the number of eggs per female flies. More eggs mean fewer larvae kept in the rearing unit. These retained larvae are placed into the nursery container and are fed for another two weeks until they will merge into prepupae and follow up on another larvae production (Dortmans B.M.A. 2017).

Pupation

The prepupae have instincts to find a dry location to pupate. The nursery container is always placed in a transfer container with a dry, water-absorbing material, which, for example, can contain mostly compost. Furthermore, the prepupae can quickly bury into that and merge to pupae (Dortmans B.M.A. 2017).

The pupation process is placed in the cages, which are as dark as possible, so-called dark cages. These cages are also protecting against changing environmental conditions such as temperature, moisture, or air movement. These cages are seen in Figure **19**, on the left side are containers with pupation stacked in the dark cage, and on the right side is a so-called love cage, where the adult flies reproduce (Dortmans B.M.A. 2017).

Figure 19: Dark cages **(Dortmans B.M.A. 2017)**

After around two to three weeks, the pupation starts to have a bit drier skin, which will make it much easier to crawl out of the pupal skin and fly out of the pupation container and stay there. The darkness inside of the cage will make sure that freshly emerged flies will not start to reproduce and will remain motionless. After releasing adult flies into love cages, due to the light, they will try to find a mate and reproduce (Dortmans B.M.A. 2017).

Ten days after larvae were put into the pupation container, the emerging into adults will start. This is shown in Figure **20**. The whole life span of BSF is approximately 25 days.

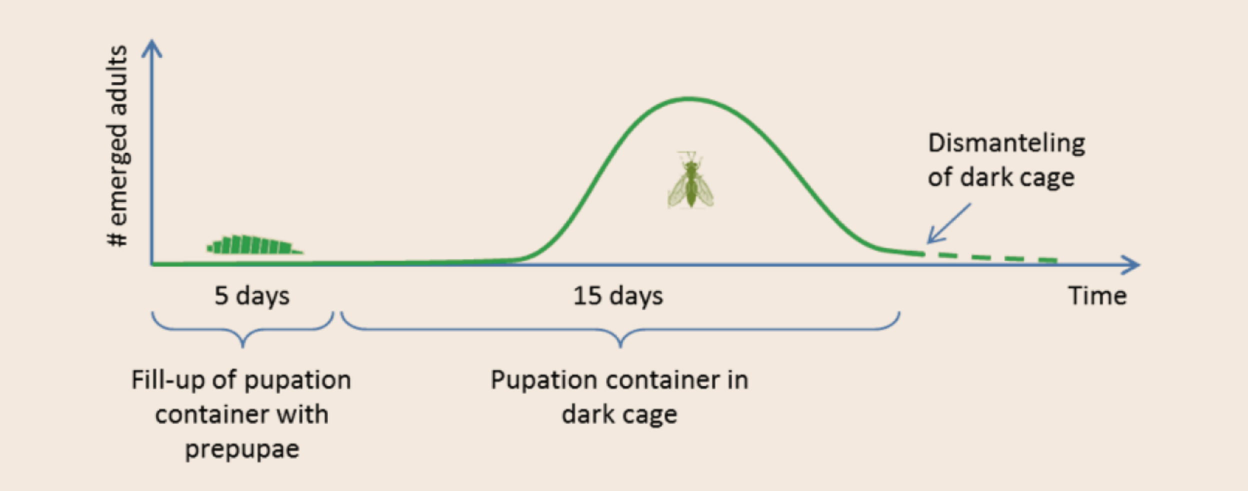


Figure 20: Dynamics of pupation of Black Soldier Flies **(Dortmans B.M.A. 2017)**

Mating

When the time comes, dark cages are connected with the love cages via a tunnel. The love-cage is lighted by consistently light and hanged in a mobile frame. The light will attract the BSF to fly into the love-cage from the dark cages. The love-cage is usually connected with three or four dark cages, and it is for recently emerged adult flies. The harvested flies are mostly the same age. The same-aged flies have one huge benefit: they are copulating and laying eggs at the same time, thus allowing for more efficient handling of eggs inside the eggies. The love cages always have wet clothes for hydration, the flies, eggies for eggs, and a box with a smelly attractant (Dortmans B.M.A. 2017).

1.6.2 Waste pre-processing and receiving unit

BSF larvae are not demanding when it comes to feeding. The water content of biowaste has to be between 70 % to 90 % and specific size of feed. As was already mentioned many times, larvae do not have chewing mouthparts, so the feeding substrates must be more suitable. The biowaste has to be shredded to become a perfect size for eating. Table **1** shows the most suitable types of biowaste for BSF treatment. Larvae depend on symbiotic microorganisms in the waste. These microorganisms degrade the cell structure and then make nutrients available for BSF larvae. If suboptimal feed were chosen, the development of larvae would be slower. However, it is vital to keep in mind that correct feeding techniques are essential from an economic perspective (Dortmans B.M.A. 2017).

Table 1: Suitable different types of waste for BSF treatment

Municipal waste	Agro-industrial waste	Manure and feces
◦ Food and restaurant waste	◦ Spent grains	◦ Pig manure
◦ Municipal organic waste	◦ Food processing waste	◦ Fecal sludge
◦ Market waste	◦ Slaughterhouse waste	◦ Poultry manure
		◦ Human feces

The biowaste should be purely organic and biodegradable for waste receiving facilities. When biowaste is coming into the facility, it is crucial to control the waste to ensure there are no hazardous materials and inorganic substances. A few plastic bags can easily be removed; however, it is important to keep in mind that any hazardous contaminants could affect the whole batch of waste, living organisms inside, workers, and larvae (Dortmans B.M.A. 2017).

The next step required a hammer mill or shredder for the incoming waste. Biowaste must be shredded in a particular size, which is smaller than 1-2 centimeters in diameter. This shredded waste helps larvae eat and grow, and be more efficient with reducing waste. Shredded biowaste increases the surface area for growing associated bacteria, which are essential in the waste (Dortmans B.M.A. 2017).

After the waste shredding comes water content control, biowaste should have water content, around 70 % to 90 %. It has been discovered that 80 % of water content is the perfect solution for larvae. If the water content is higher in the waste, then it is necessary to dewater it. Dewatering processes can be secured actively or passively. The passive way is by gravitation on the sieves or in the clean clothes hung over the bucket, where water is leaking. The active way is by using vibrating machines, where, due to vibrating, water will separate from the waste and create perfect water content. Determination of water content can be done by squeezing a handful of biowaste, and if a few drops of water will drop between fingers, then it is perfect. If it is less than a few drops, then the waste is too dry, and water needs to be added (Dortmans B.M.A. 2017). If water needs to be added to the waste matter, it is necessary to use the equation for moisture content, to make sure it has the right percentage of water. Equation **1** for moisture content is shown below the text.

Equation 1 Moisture content

$$Moisture\ content\ [\%] = \frac{W2 - W3}{W2 - W1} * 100$$

where:

W1 – the weight of the container
W2 – the weight of the container and biowaste before drying
W3 – the weight of the container and biowaste after drying

Different methods of dewatering are shown in Figure **21**, where passive dewatering by gravity is placed on the left side, screw press machine is in the middle, and on the right side is a cider screw press (Dortmans B.M.A. 2017).

If biowaste is too dry, and its moisture content is below 70 %, water needs to be added or mixed with the other biowaste, which moisture content is higher than 70 %. If biowaste needs to moister, it is necessary to make sure that water does not contain heavy metals, pathogens, or other anti-nutritional elements (Dortmans B.M.A. 2017).

Figure 21: Different methods of dewatering **(Dortmans B.M.A. 2017)**

The moment biowaste arrives at the facility is the best time to shred and measure weight. Shredded biowaste should be stored in provisory containers until it will be moved to the treatment unit where larvae are fed with it (Dortmans B.M.A. 2017).

1.6.3 BSF treatment unit

Every day 5-DOL are transferred to the treatment unit, where they are placed into containers, which already contain a specific amount of biowaste. The amount of biowaste depends on the number of 5-DOL; this can be different from day to day. As a good rule, the project FORWARD, the BSF treatment facility in Indonesia, is using 10.000 of 5-DOL larvae to feed on 15 kg of biowaste for 12 days in total (Dortmans B.M.A. 2017).

During feeding and growing of 5-DOL, waste is added three times during the 12 days so that on the 13th day, BSF larvae were ready for harvesting. Biowaste is added on the first day, the fifth day, and again on day eight, until the larvae are developed enough for harvesting (Dortmans B.M.A. 2017).

It is suggested to put 40.000 of 5-DOL per 1 m^2 treatment area, which will be fed by 60 kg of biowaste over 12 days. If there is too much biowaste in the containers, the unprocessed waste can build up heat through bacterial activity and make an uncomfortable environment for BSF larvae. However, too much waste can also attract the attention of other flies. If there is less biowaste than it is required, larvae can start to starve, and it will slow their development and make an impact on the whole treatment facility. It is necessary to check how thick the layer of biowaste is when adding more biowaste to the containers on a day five and eight. If the layer of biowaste is over 5 centimeters, it would be difficult for the larvae to process it entirely, and the bottom layer would be unprocessed (Dortmans B.M.A. 2017).

Figure 22: Containers with BSF larvae **(Dortmans B.M.A. 2017)**

It is essential to keep enough distance between containers with larvae for enough airflow, as Figure **22** shows. If the containers with larvae are too close to each other, ventilation will help this situation and allow the moisture-saturated air to be exchanged. However, for the well-being of the larvae, it is recommended to have open space between containers and enough oxygen. Enough oxygen will help to increase evaporation, and as a result, there will be a crumbly waste, which is easy to sieve from the larvae. The intensity of active ventilation needed will be different in each country because it depends on the air humidity and moisture content of the starting material and the environment (Dortmans B.M.A. 2017).

1.6.4 BSF larvae harvesting unit

BSF larvae will reach their maximum weight after 12 days in the container with biowaste. After this time, larvae will be harvested at the harvesting unit. Larvae are harvested before they transform into prepupae. Each container with larvae is weighted before harvesting, then the biowaste and the larvae need to be weighed separately, to monitor the treatment performance of waste reduction. The process for harvesting is the separation of larvae from biowaste passively or actively. The passive way is by manual sieve, which is less effective than the active way by automated shaking sieve, Figure **23**. During a higher shaking frequency, the larvae cannot crawl through the mesh on the sieve, because it is a difficult position for them. By choosing automated shaking sieve, it is possible to use a bigger mesh size on the sieve and archive higher shaking frequency than using a manual sieve (Dortmans B.M.A. 2017). It was chosen that in Danish and the Czech facilities, automated shaking sieves will be used, and Indonesian and Vietnamese facilities will manual sieves be used. This decision is based on the financial situation in each country.

Figure 23: Automated shaking sieve on the left side, manual sieve on the right side **(Dortmans B.M.A. 2017)**

The suitable size for automated shaking sieve would be 5 millimeters and 3 millimeters for manual sieve. The sieve is placed at an angle for a better slip. The containers with larvae and biowaste are emptied on that sieve. The larvae will stay on top of the sieve, and the residue from the biowaste will fall through the sieve into recipients, while the sieve is shaking. The larvae are led to a lower angle due to the sieve angle, which is connected to a bucket where the larvae fall into (Dortmans B.M.A. 2017).

If the water content of the biowaste would not be in the ideal form (80 %), then the container right before harvesting would contain the larvae with a liquid slurry of processed biowaste with some undigested chunks, instead of a crumbly waste residue. In such a case, a non-shaking flat screen with 5 millimeters mesh is recommended during the harvesting procedure. Under a non-shaking screen, a bucket or container is placed. The container with larvae and waste residues is spread out on the flat screen, while liquid residues flow through it as well as larvae because they want to avoid the direct sunlight. The larvae will eventually fall into a bucket or container as well. Larger pieces of waste residue that did not flow through the screen will stay on the top of the sieve and be removed. Larvae can be removed with a large strainer spoon from the bucket or container placed under the screen, and then transferred to a drying container with coco peat. The drying container's content should be from some dry material where larvae can dry and stay for around a day. This step will allow larvae to empty their guts and clean their skin; this adds to the quality of the end-product (Dortmans B.M.A. 2017).

1.6.5 Post-treatment unit

After harvesting, larvae can be sold in the form of pellets or alive. This depends on the requirements of the customer. It was assumed that production in the post-treatment unit would be different for each country. Therefore, 100 % of larvae will be pelletized in Denmark and the Czech Republic as the final product. In Vietnam and Indonesia, it is assumed that all larvae will be sold as a live product. BSF larvae are rich in protein, so it is an excellent substitute for soybean protein in animal feed, or it could be mixed with other nutrition ingredients for animal feed production. In the case of a mixture, the feed can be directly mixed in the pelletizing machine and produce the final form of animal feed, Figure **24**.

Figure 24: Pelletizer for animal feed

In most cases, it is necessary to perform post-treatment to make sure that larvae are sanitized and ready to be stored and transported to the customer. It is recommended to sanitized larvae; this would involve killing all bacteria which might adhere to the larvae skin. It is necessary to make sure that larvae emptied their guts, which contain digested residue. For sanitizing, it is recommended to dip the larvae in boiling water for approximately two minutes, instantly killing the bacteria and sanitizing the product (Dortmans B.M.A. 2017).

There are many ways to produce the end-product; thus, it would require different equipment and steps. This depends on the request from the customer and the market demand. For example, freezing larvae would be much easier for storage, but it would take higher energy consumption. Drying larvae would decrease the water content, and thus, it would improve the storage potential. The BSF larvae contain around 30 % of oil, a prolonged storage period of dead larvae could change the oil rancid. To avoid this problem, there is a procedure of defatting dried larvae. This process is done by using an oil press or centrifuge and then separates the larva oil from protein, which can be dried and stored much easier after that. The larvae meal has ±60 % of protein and ±10 % of fat, and then it can be a substitute in animal feed. This also depends on the farmed species, because of the amino acid, which has to be taken into account (Dortmans B.M.A. 2017).

1.7 Life Cycle Assessment

The aim of the study is a comparison between four countries. Data are collected about their current situation in organic waste management, the energy consumption of food industries, CO_2 emissions of feed production, impact on the environment, and benefits of using protein from insects.

One of the methods which are used is Life-Cycle Analysis. This technique will allow us to assess environmental impacts with all the stages of a product's life. The lifecycle of the product is from raw material through production, manufacture, use, maintenance, reuse, and disposal or recycling. LCA is also known as "from the cradle to the grave."

An LCA has four main phases, as illustrated in Figure **25**. The first phase is goal and scope definition, where it is explained why this study is made, which product or system is studied, which alternative product or system is used, and elements of scope definition.

After defining the goal and scope, it will go to the second phase, where all inputs and outputs of materials, products, resources, waste, and emissions will be collected. In this phase, the ReCiPe methodology will define two sets of impact categories, midpoint, and endpoint. There are 18 midpoint impact categories, which are based on the same amount of midpoint impact indicators (Hauschild 2017). Endpoint impact categories contain three indicators, which are human health, natural environment, and natural resources (Goedkoop January, 2008). The midpoint and endpoint impact categories are shown in Figure **26**.

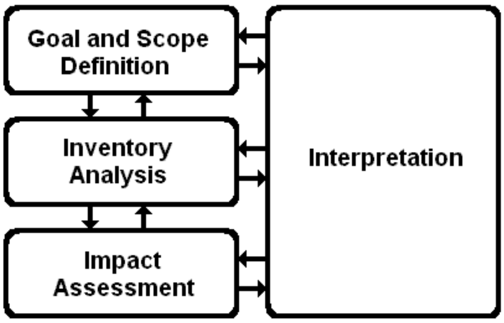


Figure 25: Life Cycle Assessment

In the third phase of impact assessment, the environmental impacts of raw materials and processes will be estimated. The environmental impact for a product or system will be assessed through different impact categories and indicator scores.

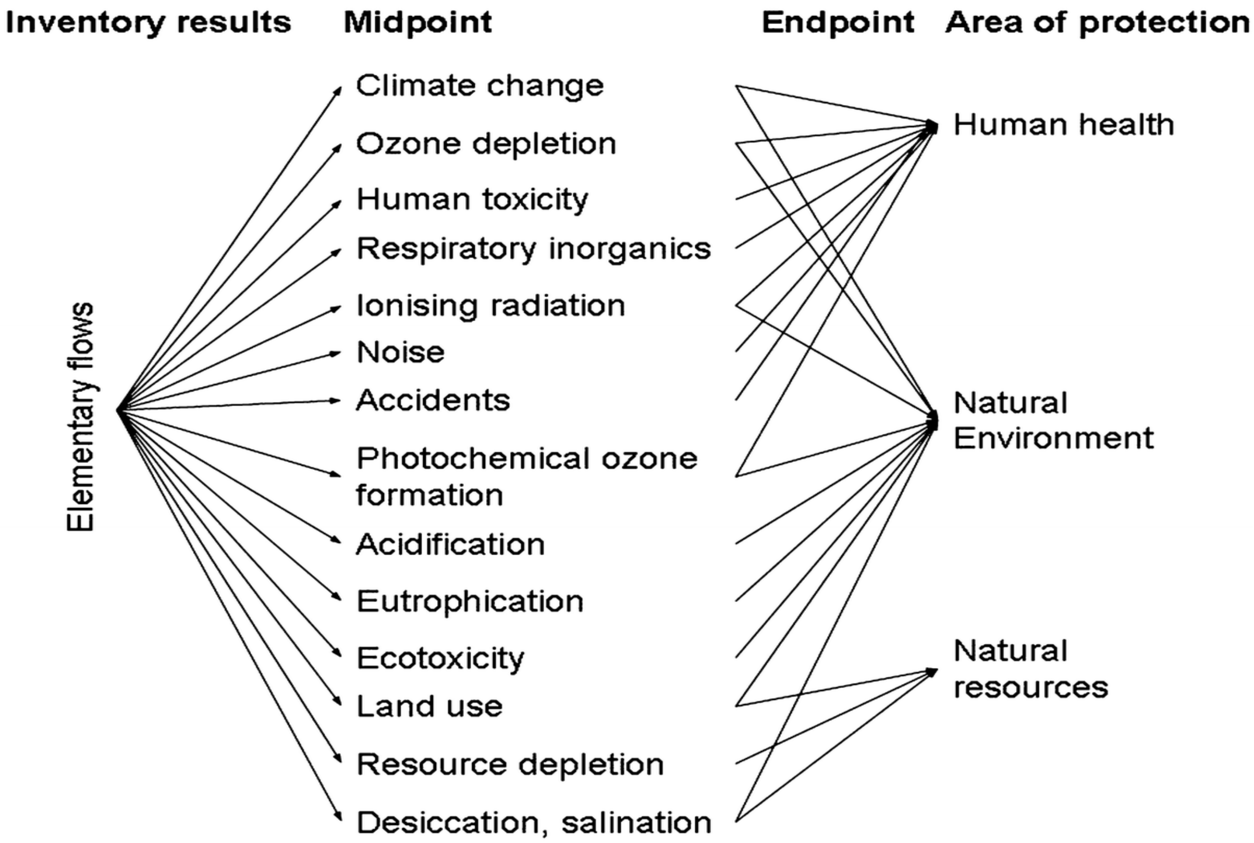


Figure 26: Impact Assessment results **(Goedkoop January, 2008)**

The last phase is the interpretation of results where it will be discussed results and compared with the other products or systems.

2. Literature review

Using insects as food is completely normal in some parts of the world. More than 2 billion people are casually cooking beetles, maggots, or caterpillars as part of their traditional food (Kupferschmidt 2015). This type of food is not entirely developed in Western Europe and North America. In these parts of the world, it is more perceived as an exotic experience in the food industry, and it is opposed to introducing the crunchy bits into their diet. Since the general population is not ready to eat insects as a portion of daily food, there is a vast potential in feeding insects to farmed animals to feed to a growing population (Bryan Lessard, CSIRO 2016).

Environmentally speaking, it is a great choice to use insects in the animal diet. Insects produce body mass at a very high rate because these coldblooded animals do not need to spend that much energy on regulating their body temperature. For example, crickets need only 1,7 kg of food to gain 1 kg of body weight, compared to regular chicken, which needs 2,5 kg of food, a pig which needs 5 kg of food or cattle which need 10 kg of food to gain the same amount of body weight. Another great benefit is that most of the types of insects can be eaten whole. Only half of the pig or chicken is edible, and with cows, less than half is edible. Gaining 1 kilogram of insect protein has less impact on the environment in comparison with rearing cattle or pigs. Rearing insects take up only one-tenth of land, compared with rearing cattle or pigs (Kupferschmidt 2015).

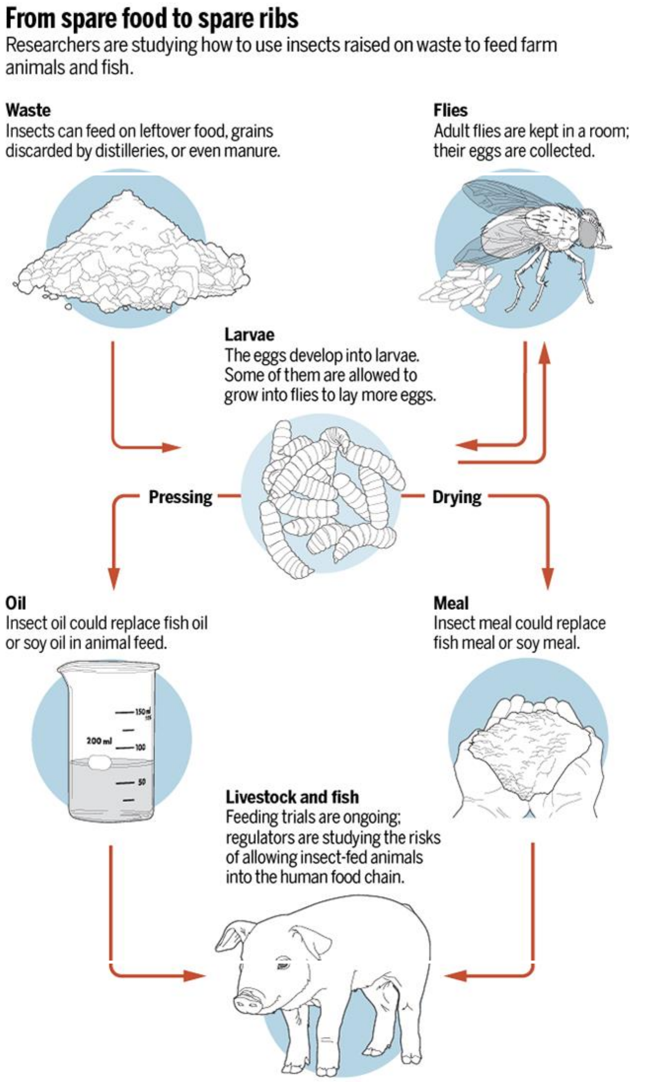


Figure 27: The Black Soldier Fly usage **(Kupferschmidt 2015)**

More than 80 % of the world's soybean is used for feeding animals. To produce one tonne of soybean, it is necessary to have one hectare of land, for the same amount of land, it is possible to produce 150 tonnes of insect protein. Insect meal could replace 25-100 % of fishmeal or soybean meal in the animal diet (Kupferschmidt 2015).

Bluebottle larvae grow on abattoir waste (hearts, kidneys, livers). In a few days, waste is covered by thousands of maggots. Another type of insects are houseflies, which feed on fresh manure. The flies lay eggs all over the manure, and within hours, the larvae can hatch from the eggs. In a few days, the larvae move toward the side, which means that they are ready to harvest. Some of the maggots are used for laying more eggs, but most of them are used for animal feed. The maggots, which are used for animal feed, are sieved from manure, then left to dry for insect powder. The maggots can also be used for oil by pressing them, as Figure **27** shows (Kupferschmidt 2015).

One of the studies of insect ingestion focused on examples of soya, insect and whey protein, and research on human blood reaction. The AA powder in soya and insect protein was comparable. It showed that insect protein was slower digested than soya protein. Further research showed that there are differences in insulin response after the ingestion of the protein supplementations. These results show that insect protein partly induces similar increasing concentration EAA in the blood as soya protein; however, digestion and insulin response is rapidly slower and more moderate than the characteristics of casein (Mathias T. Vangsoe 2018).

Insect protein can substitute soy protein as a high-quality protein and environmentally friendly solution for human ingestion. This study shows that the quality of insect protein is comparable with soya protein results; however, it is still slowly digested. Insect protein could be a potential reasonable nutrition compensation for soya, meat, and eggs, which all are rich in protein, and a part of the human daily diet (Mathias T. Vangsoe 2018).

3. Methods

To assess the impacts on the environment from the BSF treatment facility, and compare it with other systems, an openLCA software was performed using Ecoinvent 3.3 database for background data. The database was based on protein and oil production and waste processing in Denmark, the Czech Republic, Indonesia, and Vietnam. The BSF treatment facility's energy consumption relied on the data from the facility placed in Sidojardo, Indonesia.

3.1 Life cycle Assessment

3.1.1 Goal and scope and functional unit

This thesis aims to find out if the BSF treatment facility is a better solution for the production of protein in animal feed, compared with soybean production. Furthermore, the environmental impact of the production of oil is compared. The comparison is between BSFL oil, soybean oil, rapeseed oil, and palm oil. The third comparison is waste processing compared to residue composting from the BSF treatment facility, biogas production, composting, and incineration process.

Four different countries have been compared to see the differences in their economic situation, waste management, environment, and energy consumption. Even though Denmark and the Czech Republic are EU developed countries, both still have some differences. Denmark does not produce soybean for feeding livestock. It is imported from Argentina and Brazil, compared to Czech, which is producing soybean on their land, and only part of the total use of soybean is imported from

European countries. If we are going to talk about primary energy sources, Denmark uses more renewable energy, mostly from wind power. Czech does not have that many renewable resources for producing energy and instead uses mostly coal.

Indonesia and Vietnam are still developing countries that have destitute economic situations, waste management, and low living standards compared to Denmark and the Czech Republic. Soybean production in Vietnam is decreasing due to a change in the Vietnamese diet, which consists of more meat than ever been in their diet before. Soybean is mainly used for livestock feed because they are rich in protein; however, BSF larvae have huge potential in those countries because they are also very rich in protein, and animals can eat entire larvae.

Therefore, the functional unit (FU) was set up for 1 kg of biowaste as input for waste processing. The comparison between BSF facility – residue composting, composting, biogas production, and incineration process is described in more detail in section 1.3. Furthermore, for feed and food production, 1 kg of protein and 1 kg of fat as an output value was set up as a FU. Feed production is a comparison between BSF facilities in four countries and soybean production. Both have different inputs and outputs of energy, materials, and emissions. The production of oil is compared to BSFL oil, rapeseed oil, palm oil, and soybean oil.

3.1.2 System boundaries

This study mainly focuses on the BSF treatment facility. The BSF treatment facility is based on the production of protein for animal feed and oil production. There is also a comparison of three different processes for the treatment of 1 kg of biowaste, which is not included in system boundaries for protein and oil production.

The system boundaries used in the study for the BSF facility are shown in Figure **28**. The system starts with separated household biowaste because it is an input to the BSF treatment facility and ends with the compost produced from the biowaste residue.

All aspects of waste generation, collection, and transport are divided into two systems. One system is based on the biowaste market as an input of non-utilized biowaste, which refers to Indonesia and Vietnam. The other system is based on utilized biowaste as an input to the treatment facility, which refers to Denmark and the Czech Republic. Also, compost transportation to customers and fuel for transportation of biowaste from the market are not considered in the LCA. Due to the low market demand in Indonesia and Vietnam for soil improvers or fertilizers, compost is expected to be a landfill cover, considered neither negative (leachability) nor positive impacts (oxidation of methane) were taken into account.

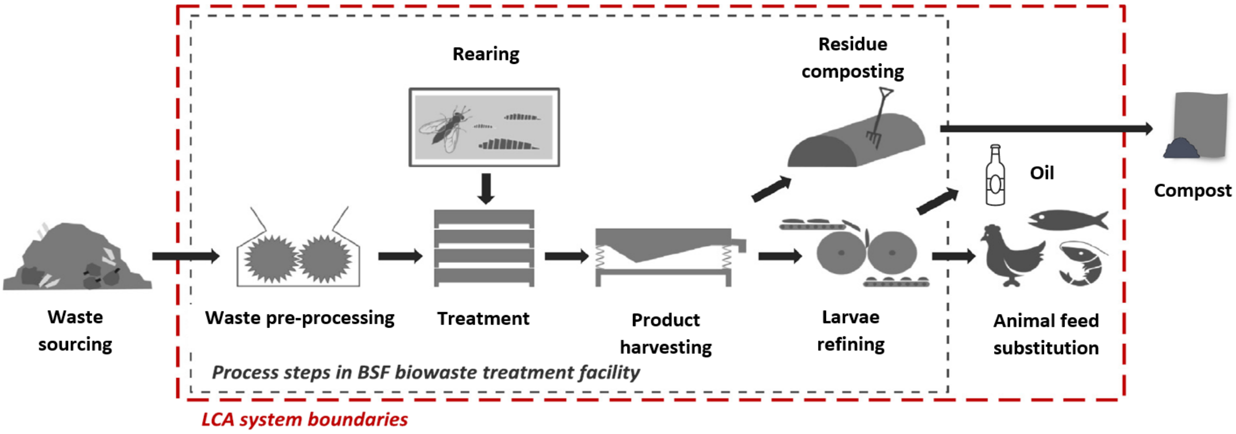


Figure 28: System boundaries for BSF facility **(Adeline Mertenat 2018)**

It has been assumed that the produced larvae meal substitutes soybean meal, using available data from the Indonesian BSF facility (Dortmans B.M.A. 2017). This study of BSF treatment facilities is divided into two scenarios. One scenario is based on the source of protein in animal feed production. The other scenario is based on oil production. Potential benefits from BSF derived oil are considered in this study as a substitute for palm oil, soybean oil, or rape oil.

Direct carbon dioxide (CO_2) emissions from BSF treatment facilities during all processes are not considered in the inventory analysis. The only emissions that have been considered in inventory analysis are nitrous oxide (N_2O) and methane (CH_4), which are part of the GHG emission.

3.1.3 Life cycle Inventory (LCI)

All systems analyzed are briefly described below the text, and the assumptions, with relevant references, are summarized in Tables below the text. For background data such as energy, electricity, water supply, Ecoinvent 3.3 database was used.

Nutrition values of BSF larvae and soybean are shown in in Table **2**. These data were used to calculate 1 kg of protein used in animal feed and 1 kg of fat used for oil production. These data were taken as average values from relevant references, which are summarized in Table **2**.

Table 2: Nutrition values of BSF larvae and Soybean

	Dry matter [%]	Protein [%]	Fat [%]	References
BSF larvae	90,97	37,8	34	(EnviroFlight 2020) (Gloria Patricia Arango Gutiérrez 2004) (Eric Van Heugten 2019)
Soybean	88	36	18	(Chubby mealworms 2020) (Snowdon 2020) (Atli Arnarson 2019)

Black Soldier Fly treatment: Energy and water consumption for different processes are assumed and based on the BSF treatment facility in Indonesia in Sidoarjo (Dortmans B.M.A. 2017). Also, it is adapted to a treatment capacity for 28,53 kg and 28,94 kg of household biowaste. The biowaste input of 28,53 kg for protein production and 28,94 kg of biowaste for oil production.

Rearing: Rearing of the flies takes place in the nursery, separated from the waste treatment process. The rearing process consists of four phases. In the first phase, flies are mating and laying eggs in the cages. Then in the second phase, larvae hatch from the eggs and grow into larvae until they are five days (these are called 5-DOL). After five days, a large part of 5-DOL is transferred from the rearing section to the waste treatment process. In the third phase, the rest of the 5-DOL larvae are further fed until they will emerge into their prepupae stage. The fourth and last phase, the larvae continue in their growing phases.

In the pupae stage, larvae will bury themself and emerge into flies; it is called pupation, and then flies fly in the dark cages, repeating the whole cycle.

Most of the electricity consumption is from ventilation and lighting. The ventilation is required to ensure the fresh air circulation inside the rearing room, and it is required for all four countries. Electric lights are required to attract flies from the dark cages into the mating cages. Water with compost is mixed in the electric mixer and used to prepare the attractant material placed in the mating cages. Chicken feed is used to feed larvae after hatching from eggs for another five days that are kept in the rearing room until they reach the prepupae stage. The data presented in a comparison between soybean production and BSF facility is calculated for 1 kg of protein. 1 kg of protein production in the BSF facility and soybean production has different inputs and outputs. The data for the BSF treatment facility are shown in Table **3**.

Table **3** and Table **5** are derived from the larvae production facility treating 28,53 kg of biowaste for production of 1kg of protein and 28,94 kg of biowaste for production of 1 kg of oil. Direct gas emissions from 5-DOL larvae are taken into account, and it is shown in Table **3** and Table **5**.

The total electricity consumption of protein and oil production is 2,62 kWh in all four countries.

Waste pre-processing: Household biowaste arriving at the BSF treatment facility is not segregated, and therefore it is required to use a shredder. It is assumed that biowaste has a perfect moisture content (80%) and therefore is not required to use a dewatering process.

Most of the electricity consumption is used for a shredder and high-pressure washer. The washer is required for the cleaning part, and therefore water supply is necessary. It is assumed, 0,2 kg of MSW will be generated from the protein and oil production. The amount of MSW is assumed by biowaste checkout after it arrives at the facility.

Treatment: Waste treatment takes place in plastic containers built on top of each other in stacks placed in the treatment room. A specific amount of 5-DOL from the rearing unit is placed into containers that already contain a specific amount of biowaste. The larvae consume a biowaste and therefore grow. It is assumed that one container contains 10.000 larvae and 15 kg of biowaste. Direct gas emissions from containers filled with larvae are taken into account, and it is shown in a comparison between soybean production, and BSF facility is calculated for 1 kg of protein. 1 kg of protein production in the BSF facility and soybean production has different inputs and outputs. The data for the BSF treatment facility are shown in Table **3**.

The treatment takes in a total of 13 days. Larvae are transferred to the harvesting room on the 13th day.

Most of the electricity consumption is used by ventilation, which is required for fresh air circulation inside the treatment room with containers filled with larvae and biowaste. The lesser part of electricity consumption is used from a high-pressure washer, which is required for the cleaning part of this process. The total electricity consumption is 7,29 kWh for both systems of protein and oil production in all four countries.

Product harvesting: After 13 days, the larvae are transferred to the harvesting unit. Larvae can be manually or automatically separated from waste residues using a sieve. Furthermore, in Denmark and the Czech Republic, larvae are separated from waste residues by an automatic sieve machine, and in Indonesia and Vietnam, are larvae separated on the manual sieve. During manual separation, larvae and waste residues are spread out on the sieve, where larvae crawl through the sieve's holes to a bucket below to avoid the direct sunlight. During automatic sieve machine, larvae and waste residues are also spread out on the sieve, but then waste residues fall into a bucket below. After separation, larvae are washed with water and left in the container filled with coco peat to dry.

Most of the electricity consumption is used by a high-pressure washer, which is required for washing larvae after separation from waste residues. A sieve machine uses the lesser of electricity consumption. Water supply is necessary for washing larvae and cleaning. The total electricity consumption for the production of oil and protein is 0,068 kWh for Danish and the Czech facilities, and 0,066 kWh for Indonesian and Vietnamese facilities.

Post-treatment: It is required that harvested larvae are placed into boiling water for 1-2 minutes to kill unwanted bacteria and sanitize them. The sanitization kills the larvae during the process; therefore, this is only considered in Denmark and the Czech. In Indonesia and Vietnam, the larvae are washed and placed in a container so they can empty their guts and be ready to sell to customers.

Another possibility is to dry the larvae after they have been boiled and sell them dried. Drying oven is used for drying larvae in Denmark and the Czech Republic. It is assumed that after drying in an oven, all larvae are pelletized in a machine and packed into paper bags in Danish and Czech facilities. On the contrary, in Indonesian and Vietnamese facilities, there will not be used a pelletized for larvae, and therefore, larvae will be sold alive or as whole dried larvae.

In Denmark and the Czech Republic, electricity consumption is used by heating water, drying, pelleting, packaging, and from a high-pressure washer. The electricity consumption is used by mechanical pressing for oil extraction. It is only included in Table **5** of oil production in all four countries. Water supply is required for boiling water and cleaning for all four countries. It is assumed, 1 kg of MSW will be generated from protein and oil production.

Table **3** and Table **5** for oil and protein production include electricity consumption for all processes in Denmark and the Czech Republic. The required electricity consumption for oil production is 0,62 kWh for Indonesian and Vietnamese facilities, and 1,6 kWh for Danish and the Czech facilities. Furthermore, the required electricity consumption for protein production is 1,29 kWh for Danish and Czech facilities, and 0,32 kWh for Indonesian and Vietnamese facilities.

Residue composting: After the larvae are harvested, the waste residues are composted by using the same approach as a typical biowaste composting process, as presented further in the comparison of waste processing. The biowaste residues from protein production are 9,16 kg, and 9,29 kg of biowaste from oil production. Emissions and energy consumption from residue composting are not included in the comparison of protein and oil production. Residues composting is included in the comparison between typical composting, biogas production, and biowaste incineration, which is more detailed described further in the comparison of waste processing.

Additional processes: The BSF facility required regular cleaning of all equipment. Therefore, energy and water consumption of washing machines, high-pressure washer, and heating water are considered in LCA. A wastewater treatment facility treats the wastewater, and MSW is treated by a treatment facility for MSW.

Animal feed substitution: Harvested BSF larvae are assumed to substitute current soybean in animal feed, also to substitute soybean oil, rapeseed oil, and palm oil in the production of oil.

Protein production

A comparison between soybean production and BSF facility is calculated for 1 kg of protein. 1 kg of protein production in the BSF facility and soybean production has different inputs and outputs. The inputs and outputs for the BSF treatment facility are shown in Table **3**.

Table 3: Input/output of the BSF treatment facility – protein production

PROTEIN – BSF Larvae				
Waste Pre-processing				**Source:**
INPUT	**value**	**OUTPUT**	**value**	(Adeline Mertenat 2018) (Dortmans B.M.A. 2017), Assumptions
Biowaste [kg]	28,53	Wastewater [l]	20,00	
Energy [kWh]	0,30	MSW [kg]	0,20	
Water [l]	20,00	Biowaste [kg]	28,53	
Treatment				
Biowaste [kg]	28,53	Larvae [pcs]	13.182	
Energy [kWh]	7,30	Wastewater [l]	15,00	
Water [l]	15,00	Larvae weight [kg]	2,90	
		Emissions - CH_4 [kg]	1,14E-05	
		Emissions - N_2O [kg]	2,45E-04	
Rearing				
Energy [kWh]	2,62	Wastewater [l]	25,00	
Water [l]	30,00	Biowaste [kg]	0,03	
Chicken feed [kg]	0,01	5-DOL to treatment [pcs]	13.182	
Coco peat [kg]	0,01	Emissions - CH_4 [kg]	1,14E-06	
Compost [kg]	1,10	Emissions - N_2O [kg]	2,45E-05	
Harvesting				
Energy [kWh]	0,07	Larvae [kg]	2,90	
Water [l]	10,00	Wastewater [l]	10,00	
Larvae [kg]	2,90	Biowaste [kg]	9,13	
Coco peat [kg]	0,0002			
Post-treatment				
Energy [kWh]	1,29	Larvae pellets [kg]	2,90	
Water [l]	15,00	Raw product [kg]	*	
Larvae [kg]	2,90	Wastewater [l]	15,00	
Packaging mat. [kg]	0,17	MSW [kg]	1,00	
		BSFL protein [kg]	1,00	

* For the BSF treatment facility in Indonesia and Vietnam

Oil production

Comparison between BSFL, soybean, palm, and rapeseed (canola) oil is based on their output value of 1 kg of oil. All types of oil have different inputs, outputs, and processes depending on their percentage of fat extracted from the plant or larvae. Table **4** shows the kcal value of each type of oil and the percentage of fat content. BSF larvae oil has the lowest calorific value per 1 kg of oil, and soybean oil has the highest calorific value per 1 kg. Table **5** shows the inputs and output of the BSFL oil production.

Table 4: Production of oil, kcal per 1 kg of oil

	Value [kcal/kg]	**Fat [%]**	**Source:**
Soybean oil	8820	18	(Food nutrition table 2020) (Canola growers 2020) (Chubby mealworms 2020) (K.C.Surendra 2016)
BSFL oil	5233	34	
Palm oil	8740	49	
Rapeseed oil	8750	35-40	

Oil production: There are various ways to extract the oil, such as cold pressing, or high-pressure high-speed presses. Cold pressing yields produce less oil than other methods. This method is more often seen in smaller specialty companies that use this process. The big oil producers tend to use solvents and high-pressure high-speed presses, which are more productive, but it also generates heat. This generated heat makes oil darker and diminishes the flavor and nutritional value. The residue, so-called cake, can later be used in animal feed production, composting, or for biogas production. Once the oil is extracted, oil has to go through the filtration system.

Table 5: Input/output of the BSF treatment facility - oil production

FAT – BSF larvae				
Waste Pre-processing				**Source:**
INPUT	**value**	**OUTPUT**	**value**	(Adeline Mertenat 2018) (Dortmans B.M.A. 2017), Assumptions
Biowaste [kg]	28,94	Wastewater [l]	20,00	
Energy [kWh]	0,31	MSW [kg]	0,20	
Water [l]	20,00	Biowaste [kg]	28,94	
Treatment				
Biowaste [kg]	28,94	Larvae [pcs]	13.369	
Energy [kWh]	7,30	Wastewater [l]	15,00	
Water [l]	15,00	Larvae weight [kg]	2,94	

		Emissions - CH_4 [kg]	1,14E-05
		Emissions - N_2O [kg]	2,45E-04
Rearing			
Energy [kWh]	2,62	Wastewater [l]	25,00
Water [l]	30,00	Biowaste [kg]	0,03
Chicken feed [kg]	0,01	5-DOL to treatment [pcs]	13.369
Coco peat [kg]	0,01	Emissions - CH_4 [kg]	1,14E-06
Compost [kg]	1,12	Emissions - N_2O [kg]	2,45E-05
Harvesting			
Energy [kWh]	0,07	Larvae [kg]	2,94
Water [l]	10,00	Wastewater [l]	10,00
Larvae [kg]	2,94	Biowaste [kg]	9,26
Coco peat [kg]	0,0002		
Post-treatment			
Energy [kWh]	1,6	Larvae [kg]	2,94
Water [l]	15,00	Raw product [kg]	*
Larvae [kg]	2,94	Wastewater [l]	15,00
Packaging mat. [kg]	0,17	MSW [kg]	1,00
		BSFL oil [kg]	1,00

* For the BSF treatment facility in Indonesia and Vietnam

Waste processing

This comparison is based on 1 kg of biowaste as an input value. Waste processing is comparing residue composting in the BSF treatment facility, composting process, biogas production, and incineration process. Each process has 1 kg of biowaste as a FU. The output value is different in each process.

Residue composting in the BSF treatment facility

Waste handling: The handling of biowaste input is done by machinery in each country. Energy consumption of a waste shredder is considered in a BSF treatment facility; thus, it is not calculated into this comparison. Table **6** shows the inputs and outputs of residue composting at the BSF treatment facility.

Composting process: The blowers powered by electric fans are ensuring forced aeration during composting. Diesel fuel is used for a wheel loader that ensures the turning of compost heaps. After 3-4 months of composting duration, compost is sieved through an electric sieve machine. For another 1-2 months is the sieved compost product left to further mature before it is sold.

Values of direct emissions of N_2O and CH_4 from composting are taken into account (Adeline Mertenat 2018), default values of the unmonitored data are used. Table **6** shows the inputs and outputs of residue composting at the BSF treatment facility. Direct emissions of CO_2 are not considered in this process.

Table 6: Input/output of residue composting at the BSF treatment facility

Residue Composting - BSF Facility				Source:
INPUT	values	**OUTPUT**	values	(Adeline Mertenat 2018) (Dortmans B.M.A. 2017), Assumption
Biowaste [kg]	1,00	Compost [kg]	1,00	
Electricity [kWh]	0,00056	Emissions - CH_4 [g]	0,63	
Diesel [kg]	0,00022	Emissions - N_2O [g]	0,063	

Composting facility

The composting process is identical to the previous one (residue composting in the BSF treatment facility). For background data such as energy, electricity, emissions, Ecoinvent 3.3 database was used. Table **7** shows the inputs and outputs of the composting process.

Waste handling: The handling of biowaste input is considered by machinery in each country. Energy consumption of a waste shredder is considered from the Ecoinvent 3.3 database.

Composting process: The blowers powered by electric fans are ensuring forced aeration during composting. Diesel fuel is used by a wheel loader that ensures the turning of compost heaps. After 3-4 months of composting duration, compost is sieved through an electric sieve machine. For another 1-2 months, the sieved compost product is left to mature further before it is sold. The energy consumption of this process is considered in calculations.

Table 7: Input/output of the composting facility

Composting Facility				Source:
INPUT	**values**	**OUTPUT**	**values**	(Adeline Mertenat 2018) (Florian Amlinger 2007) (Antoni Sánchez 26 May, 2015), Assumption
Biowaste [kg]	1,00	Compost [kg]	1,00	
Electricity [kWh]	0,00177			
Diesel [kg]	0,0007			

Biogas production

Biogas production is set up on 1 kg of biowaste as an input value. For background data such as energy, electricity, emissions, transportation, and handling of biowaste, Ecoinvent 3.3 database was used. Table **8** shows the inputs and outputs of the biogas production.

Waste handling: The handling of biowaste input is considered by municipalities and with waste trucks in each country. Energy consumption of a waste shredder is considered from the Ecoinvent 3.3 database.

Biogas production: Biogas is produced by anaerobic digestion of organic material such as biowaste from households. It is a combination of energy production and waste treatment for reducing biowaste. It can also be used for other types of waste such as sewage sludge, manure from households and industries. In this case, the focus is on biogas production from household biowaste. When biowaste is used for biogas production, the GHG emissions from handling and storing biowaste are reduced. A by-product, such as high-quality fertilizer, is produced during biogas production. A by-product is not considered in the calculations.

Table 8: Input/output of biogas production

Biogas production				**Source:**
INPUT	values	**OUTPUT**	values	(Harshit Sharma 2017) (H. Uellendahl 2008) (Henrik B. Møller 2008) (D. Turner 2016)
Biowaste [kg]	1,00	Biogas [m^3]	0,09	
Electricity [kWh]	0,08			

Incineration process

The incineration process is set up on 1 kg of biowaste as an input value. For background data such as energy, electricity, emissions, transportation, and handling of biowaste, Ecoinvent 3.3 database was used. Table **9** shows the inputs and outputs of the incineration process.

Waste handling: The handling of biowaste input is considered by municipalities and with waste trucks in each country. Energy consumption of a waste shredder is considered from the Ecoinvent 3.3 database.

Incineration: Incineration is a waste treatment process that is reducing waste. The input value is 1 kg of biowaste, which is combusted. Biowaste is converted into ash, flue gas, and heat during high-temperature combustion. Excess heat from the process is not taken into account; thus, there is no heat recovery.

Table 9: Input/output of the incineration facility

Incineration process				**Source:**
INPUT	values	**OUTPUT**	values	(European Commission (EC) 2009)
Biowaste [kg]	1,00	Biowaste [kg]	-1,00	
Electricity [kWh]	0,142			

3.2 Data collection –Questionnaire

A questionnaire can be an effective way to get to know the opinion, references, behaviors, or attitudes of a broad audience. The Questionnaire has six questions. It is based on the age groups, country of origin, current living country, financial and general opinion on meat from pig, poultry, and cattle, which was fed by insect-based feed and plant-based feed. In total, 128 people participated in this Questionnaire.

The first question in the Questionnaire was from what country the participants came. The results show that most of the responders are coming from Denmark (44 %), Czech Republic (20 %), and Slovakia (5 %) from all of the total 25 countries represented. This is shown in Figure **29**. Most of the participants are from Europe, but there are a small number of participants from Australia, Philippines, Afrika, India, and Turkey. It is essential to know the opinions of other nationalities, which habits they have, and if it is comfortable for people to try and if they can get used to the new way of feeding animals.

The reason for this study was explained in the Questionnaire, so the correspondent knew the topic and the case. The topic and the case were to prevent the enormous growth of soybean on agriculture land, decreasing GHG emissions of farming, use the agriculture land perhaps for some other plants, or the usage of soybean for human consumption.

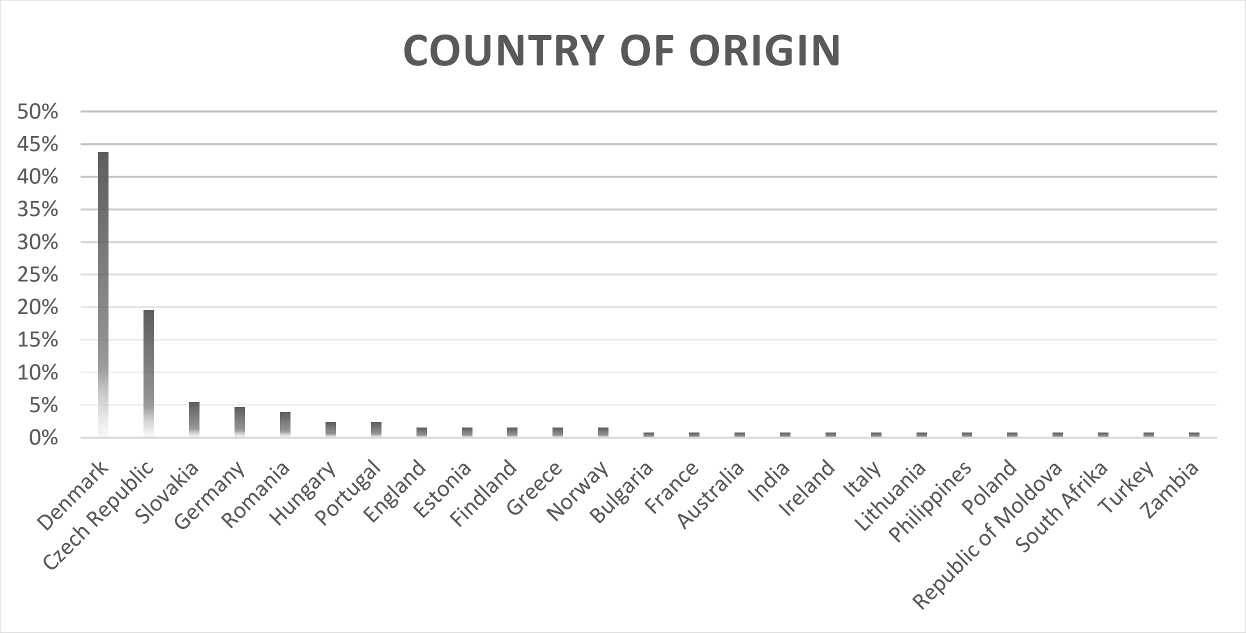


Figure 29: Questionnaire – Country of origin

The second question was in what country all participants currently live. Most of the participants are currently living in Denmark (80 %) Czech Republic (14 %), and in the rest of the countries are shown in Figure **30**. Denmark has high standards of living, such as high income, trust, freedom, social support, healthy life expectancy, and generosity. Based on these parameters, Denmark was ranked as one of the best places to live in the whole world (Novak 2019).

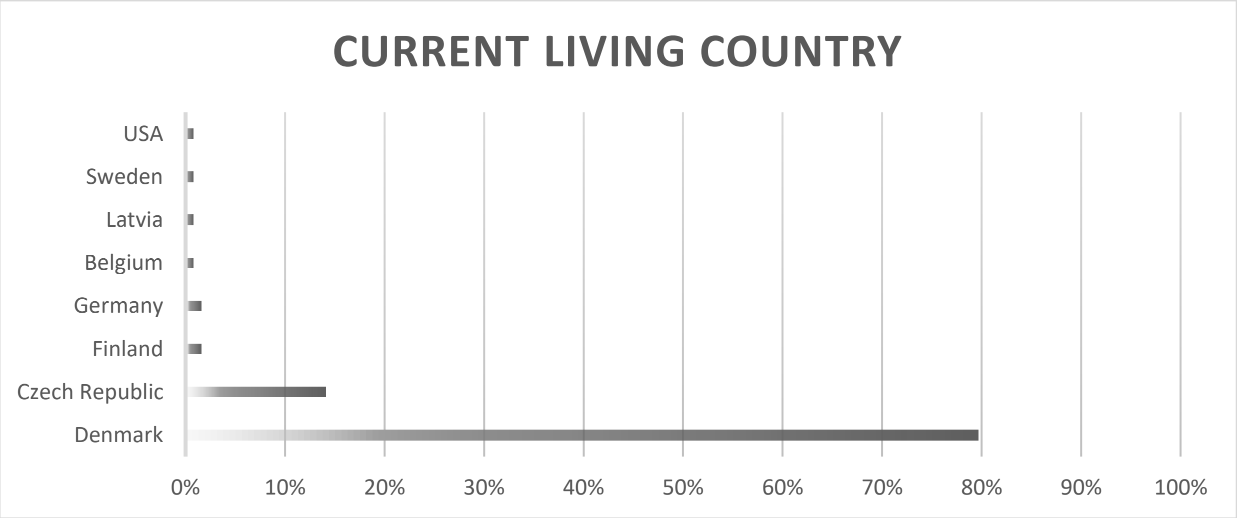


Figure 30: Questionnaire – Current living country

The third question was in which age group the participants were (Figure **31**). This question is crucial for obtaining the information about what age group answers the questions and what age group is willing to approach the new technology of animal feeding. The results show that 51 % of participants are in the age between 20-25, then 23 % responders are between 26-29, and 10 % of responders are between 30-35, and 6 % responders are above 50 years old. A lot of young people answered the questionnaire, which gives a good picture of their opinion on this topic.

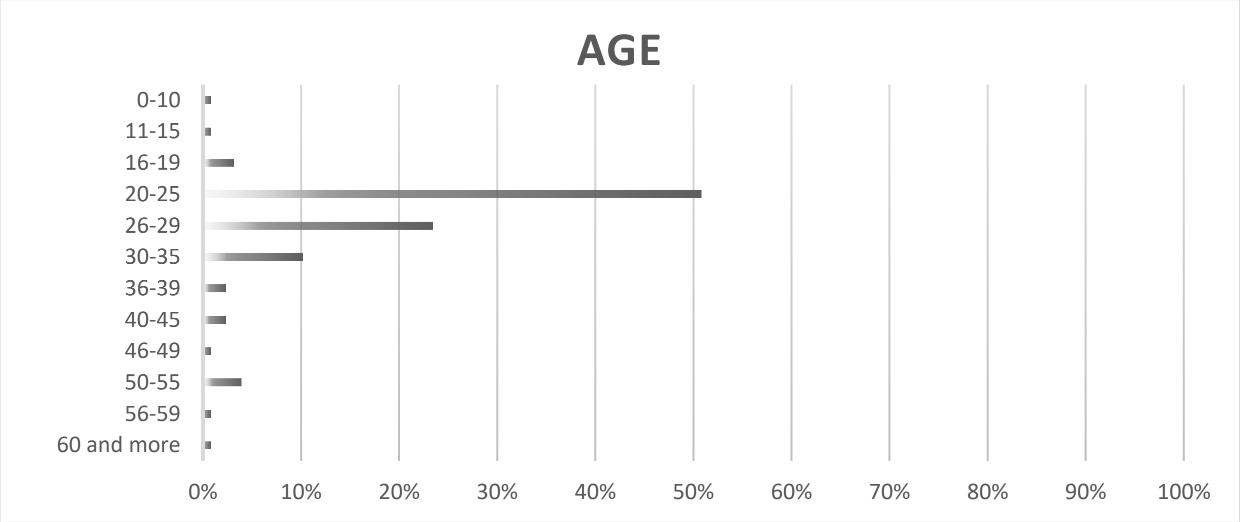


Figure 31: Questionnaire – Age category

The fourth question was if the participants would mind eating meat from cattle, pig, or chicken, which had been fed with insect-based protein instead of plant-based protein. Participants should answer on a scale from 1 to 10 if they would only buy meat that had been fed with insect-based feed, or if they did not care which feed the meat product had been fed, or they would buy only buy meat that has been fed by plant-based feed. In this question, it was mentioned that insect-based feed for animals is more environmentally friendly than meat fed with usual plant-based feed. Furthermore, the participant was told that there is no harm to humans if they eat meat that has been fed insect-based protein. From the results, as Figure **32** shows, 44 % responded that they do not care which feed they had been fed. 14 % of responders said they would rather buy meat from animals fed with insect-based feed, which shows the scale on Figure **32** as a third option, which is between 1 and 5. 4 % answered that they would only buy meat from animals that had been fed by insect-based feed. 6 % of responders said they would only buy meat from animals fed by plant-based feed. Overall, responders answer that they would buy meat from animals which had been fed by insect-based feed, the reason for those answers can be that insects are more environmentally friendly, and it is not changing the taste of meat.

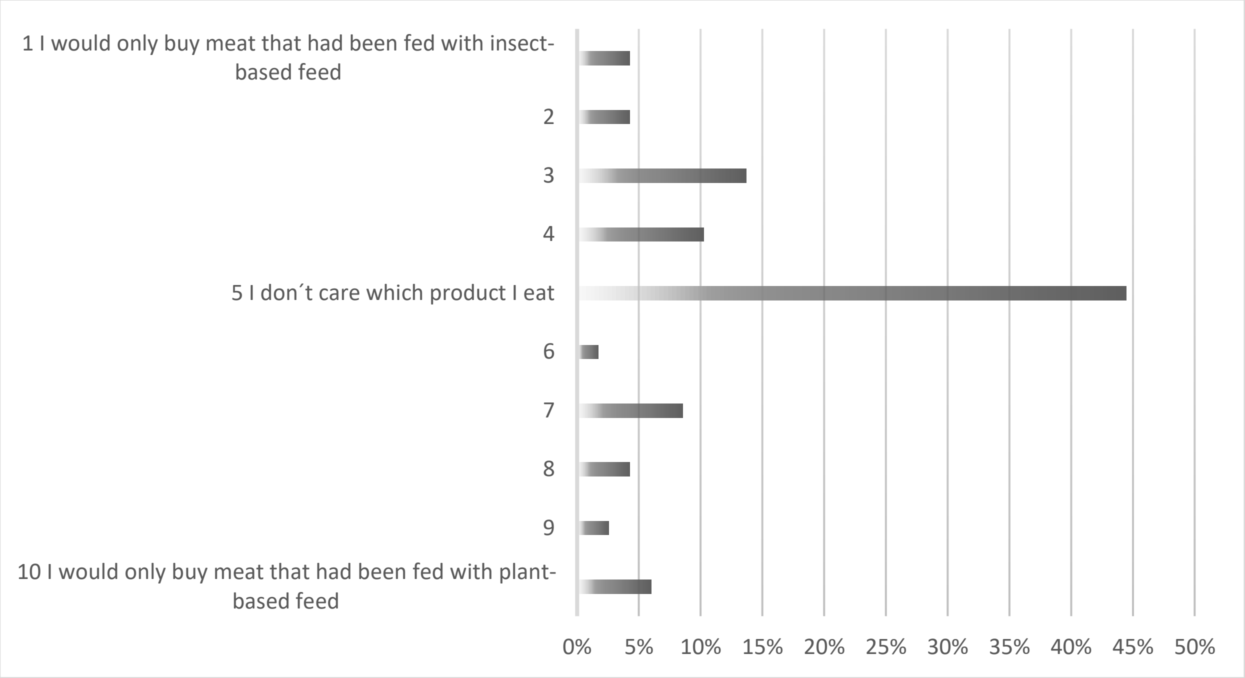


Figure 32: Questionnaire – different types of animal meat which had been fed by insect-based or plant-based protein

In the fifth question, participants could choose, on a scale from 1 to 10, if they would choose meat from cattle, pigs or chickens that had been fed with insect-based food, which is more environmentally friendly, over meat that had been fed with regular plant-based food – assuming that there is no harm to humans. As Figure **33** shows, over 50 % answered that even though the meat, from an animal which had been fed by insect-based feed, would be a bit more expensive than the meat from animals which had been fed by plant-based feed, they would still buy it. However, 38 % of respondents say that they care about the price as well, and if it would be too expensive, they would instead buy meat from the plan-based feed.

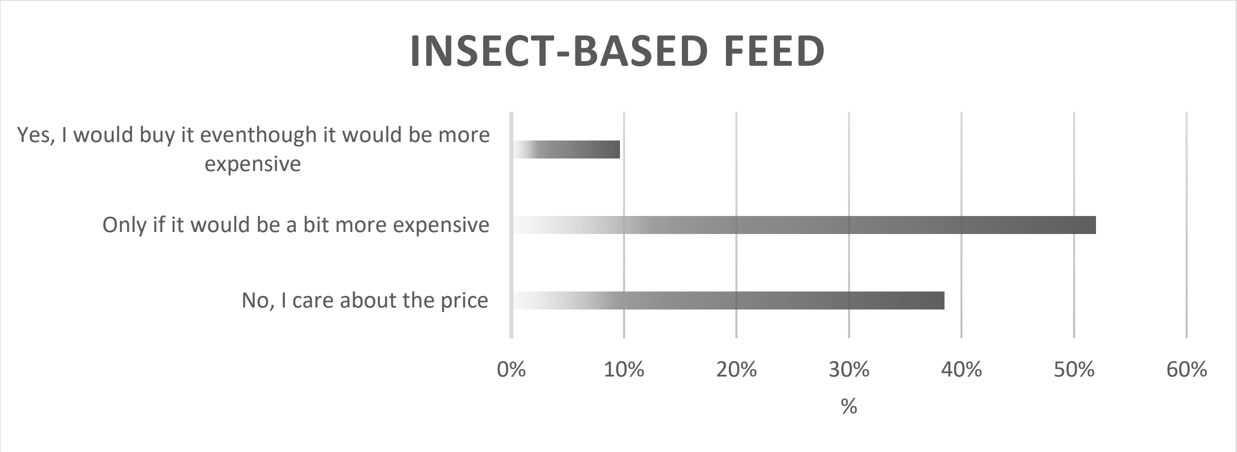


Figure 33: Questionnaire - Insect-based feed

Nevertheless, people care about the price of meat which they are buying. There are many factors why responders have that opinion. The results show that 51 % of responders are in the age between 20-25. However, if meat from animals that had been fed by insect-based feed would be a bit expensive, people in this age category would still buy it, but the price cannot be that much higher. The price of this new technology of animal feeding by insect-based feed should be at least on the same price level as meat from animals fed by plant-based feed, so people would still buy it.

The last question was the same as the previous one, but on plant-based feed, thus, the participants who answered before said that they would buy only meat from animals that had been fed by plant-based feed. From results, as Figure **34** shows, it is evident that responders care a lot about the price of meat, which they are buying. Over 40 % of respondents answered that they would still buy meat from animals that had been fed by plant-based feed even though it would be a bit more expensive than the other insect-based meat.

14 % of responders answered that they would not buy meat from animals which had been fed by insect-based feed, and they would buy only meat from animals which had been fed by plant-based feed. Insect meal is not popular in Europe and North America, and it is considered more as a new exotic experiment in the food industry, even though this Questionnaire was not about direct insect feed for humans, but animals.

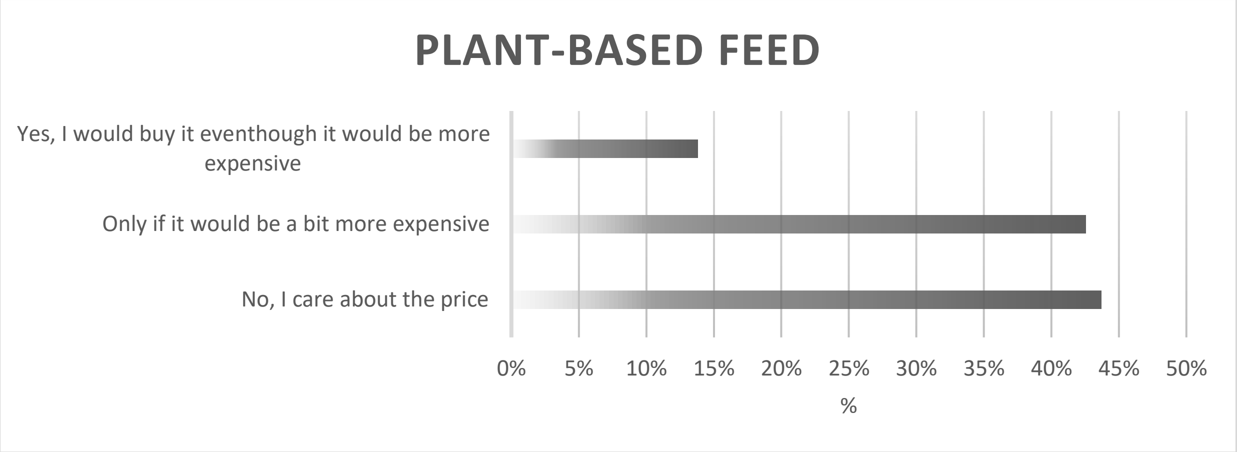


Figure 34: Questionnaire - Plant-based feed

As the results of this Questionnaire, people are aware that plant-based feed for animals is taking more land on the planet and that the food could be used for human consumption. One of the reasons why the plant-based feed is used in animal feed is that soybean is rich in protein and oil. With a growing population, meat consumption leads to planting more plants rich in protein for only animal feed. One of the causes is an increase in deforestation in the world to grow more plants that are rich in protein (Union of Concerned Scientists 2015).

Another result of this Questionnaire is that the product price does matter for people, especially in the age group between 20-29. A higher percentage of responders showed that people would buy meat from animals fed by insect-based feed, which could be better for the environment and could lead to decreasing hectares of plants rich in protein that is used in animal feed. Another advantage of using insect protein as a substitute for plant protein is the reduction of emissions that are emitted into the air, water, and soil from agriculture. Another benefit that could be taken from using insects is an oil that could potentially substitute palm oil, which is also one of the reasons for deforestation worldwide.

4. Results

This chapter will present the results from the impact assessment. The impact assessment was performed with the software openLCA.

4.1 LCA – Inventory

4.1.1 Protein production

The electricity consumption in the harvesting and post-treatment processes is different in the BSF treatment facilities in Denmark, the Czech Republic, Indonesia, and Vietnam. The market for biowaste was used only in the system for Indonesia and Vietnam, where it is assumed that the input of biowaste is non-utilized. In contrast, the input of biowaste in Denmark and the Czech Republic is utilized, due to their better waste management. The final product is assumed to be sold as living larvae to the local market in Indonesia and Vietnam. In comparison with the Danish and Czech facilities, the final product is assumed to be pelletized and sold in paper bags to the local market.

The direct carbon dioxide emissions from the larvae are not considered at the BSF treatment facilities. As a part of the GHG, nitrous oxide and methane are considered in the inventory analysis.

4.1.2 Oil production

Based on Table **5**, the BSF treatment facility in Indonesia and Vietnam has a lower energy consumption in comparison with the BSF treatment facility in Denmark and the Czech. The input of biowaste is assumed to be non-utilized in Indonesia and Vietnam, where it is utilized in

Denmark and The Czech Republic. The electricity consumption from post-treatment is 0,62 kWh for the treatment in Indonesia and Vietnam and 1,6 kWh in Denmark and the Czech Republic. The difference between the electricity consumption is because the facilities in Vietnam and Indonesia will not use pelletizer, packaging machine and material for packaging, due to they sell living larvae. Furthermore, electricity consumption is different in the harvesting unit, where the sieving machine is not used in Indonesian and Vietnamese facilities.

Direct carbon dioxide emissions from larvae are not considered at the BSF treatment facility. As a part of the GHG, nitrous oxide and methane are considered in the inventory analysis.

The only change in the systems of producing protein or oil is the post-treatment. In the post-treatment process, a mechanical pressing machine is used for oil extraction, where for protein usages, the larvae are dried, pelletized and packed.

According to the comparison of soybean production and BSF treatment facility, the energy consumption is higher at the BSF treatment facility, but soybean production is using more fossil fuels. The agricultural production of soybean is immensely loaded with fertilizers, pesticides, herbicides, and insecticides. As a benefit, the BSF treatment facility is reducing biowaste, compare to soybean production, which does not reduce any household waste.

According to the kcal value per 1 kg of oil, the highest kcal is soybean oil with 8820 kcal, followed by rapeseed oil with 8750 kcal, palm oil with 8740 kcal and BSFL oil with 5233 kcal. From a nutritional point of view, BSFL oil has the lowest calorific value per 1 kg of oil. The BSFL oil could substitute all types of oil, due to its low kcal value; therefore, 1 kg of BSFL oil can substitute 0,6 kg of palm oil, rapeseed oil, and soybean oil.

The BSFL oil can substitute rapeseed oil in Denmark and the Czech Republic. The BSFL oil can substitute soybean oil in the Czech Republic, Indonesia, and Vietnam. Finally, in Vietnam, the production of palm oil can be substituted with BSFL oil production.

4.1.3 Waste processing

Based on Section 3.1.3 of waste processing, only the residue composting from the BSF treatment facility was further studied. The biogas production, composting, and incineration process are based on the database at openLCA and compared with studied residue composting at the BSF treatment facility.

Regarding the comparison of waste processing, energy consumption is different in each process. The highest energy consumption is the incineration process when the biowaste is burned into ashes.

During the incineration process, the different methods and technologies were not considered in each country.

Direct carbon dioxide emissions are not considered at residue composting at the BSF treatment facility.

4.2 LCA - Impact assessment

At the third stage of the LCA, the environmental impacts of raw materials, processes, and services are assessed in protein production, oil production, and waste processing. The environmental impact for each system is studied through the different impact categories and indicator scores.

In this phase, the ReCiPe methodology will define two sets of impact categories, midpoint, and endpoint. During the impact assessment, several midpoint and endpoint impact categories are analyzed, and the impacts of different systems in each comparison have been compared. Midpoint impact categories include climate change, agriculture land occupation, natural land transformation, ozone depletion, water depletion, human toxicity, and marine ecotoxicity. Endpoint impact categories include the total results of the ecosystem, human health, and resources.

The impact assessment was performed with the software openLCA. This software is used for calculating and modeling the environmental impacts of the studied systems. When using this tool (software), the significant flows and processes involved in the system (from the cradle to the grave) have to be defined, as well as the market associated with these flows.

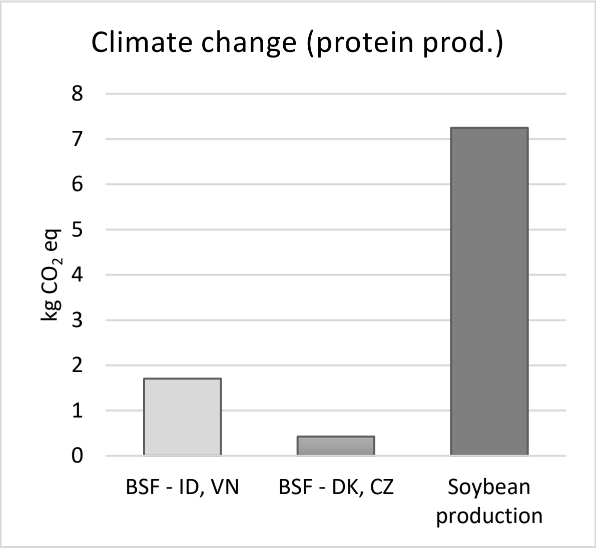
The classification and characterization of the impact categories of the three different comparisons are performed by openLCA using the ReCiPe midpoint H method. In contrast, the normalization is performed by using the ReCiPe endpoint H method.

4.2.1 Midpoint impact category – Climate change

Climate change is related to the emissions of GHG, which contribute to the rising of the surface temperature across the whole planet, thus, contributing to the global warming potential.

Protein production

Based on Figure **35**, soybean production has the most significant impact on climate, followed by the BSF treatment facilities in Indonesia and Vietnam. The lowest impact on the environment is the BSF treatment facility in Denmark and the Czech from all three systems. The most significant environmental impact in soybean production is the emission of carbon dioxide during the agricultural process and protein production. It is not only the soybean production that impacts the environment; the BSF treatment facilities for all countries also contribute to this impact category.



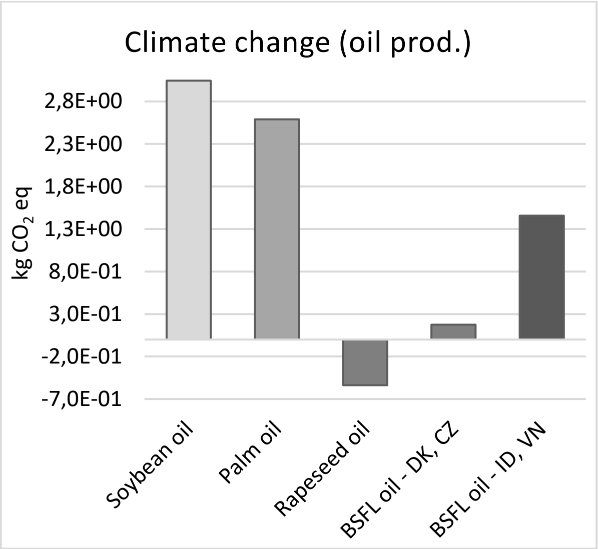


Figure 35: Climate change – protein production

Figure 36: Climate change - oil production

Oil production

Regarding climate change, the oil production with the highest impact is soybean oil, followed by palm oil and then BSFL oil from Indonesia and Vietnam (Figure **36**). As with the previous results from protein production, the most significant impact on the environment is the emission of carbon dioxide during the agricultural process and oil production. Carbon dioxide emissions are the main contributor in the production of soybean and palm oil, which have the highest impact in this category. The main contributor to emission, in the production of BSFL oil in Indonesia and Vietnam, is the carbon dioxide emissions from the market for biowaste. Although, all types of oil are contributing to this impact category, as well.

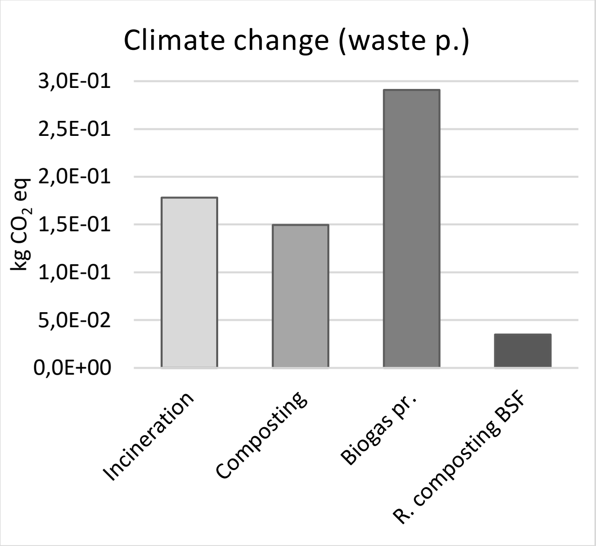


Figure 37: Climate change - waste processing

Waste processing

Figure **37** compares waste processing with the most significant environmental impact on climate change from biogas production, followed by the incineration process and then composting. Biogas production contributes to this impact category due to anaerobic digestion and carbon dioxide emissions. Nevertheless, all waste processes are contributing to this impact category.

4.2.2 Midpoint impact category – Agricultural land occupation

Protein production

According to Figure **38**, soybean production has a tremendous impact on agricultural land occupation due to the land that is necessary for planting soybean. The second-largest impact on this category is from the BSF treatment facility in Indonesia and Vietnam, where the biowaste market is the most significant contributor, due to the land necessary to store the biowaste.

The negative impact in this category is from the BSF treatment facility in Denmark and the Czech. The use of kraft paper for packaging pelletized larvae contributes to the environmental impact, but the market for electricity decreases this impact, and the total impact is a negative value.

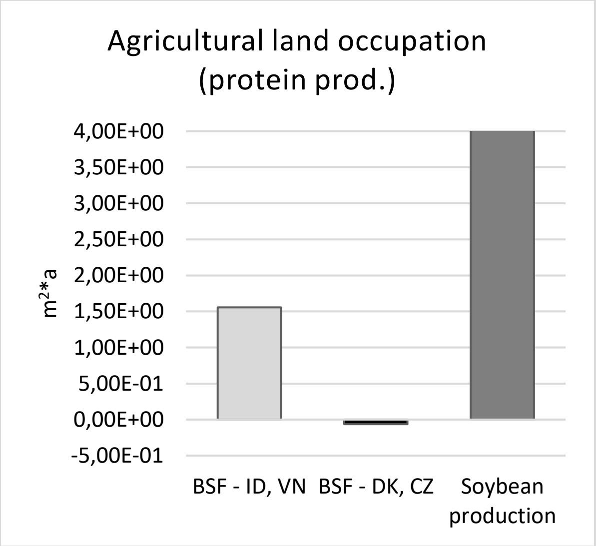


Figure 38: Agricultural land occupation - protein production

Oil production

Based on Figure **39**, the production of rapeseed oil has a tremendous impact on agricultural land occupation, followed by soybean oil, palm oil, and then BSFL oil in Indonesia and Vietnam. Finally, the BSFL oil in Denmark and Czech has the lowest impact in this category. The most significant environmental impact is the land occupation that is necessary for rapeseed production.

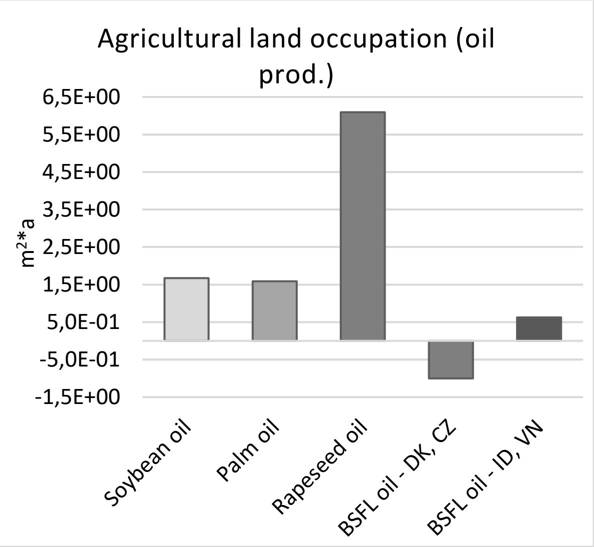


Figure 39: Agricultural land occupation - oil production

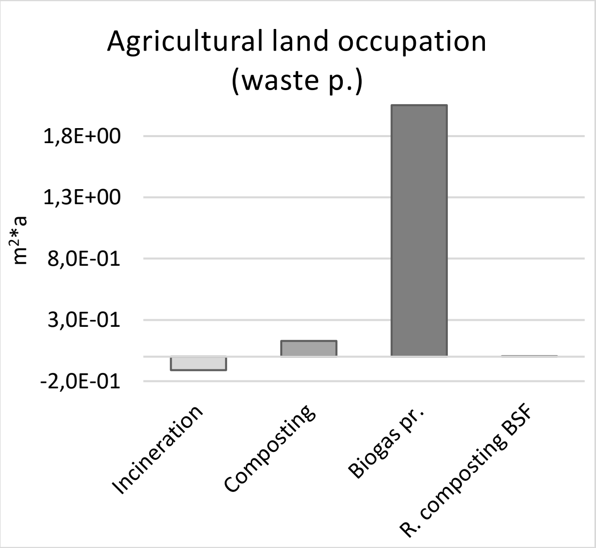


Figure 40: Agricultural land occupation - waste processing

Waste processing

Biogas production is responsible for the highest impact on agricultural land occupation (Figure **40**), with a significant difference from the other processes, such as composting and residue composting from the BSF treatment facility. The negative impact of this category is the incineration process. The negative impact indicates that this process in itself reduces waste that would otherwise end in a landfill. It is assumed the ideal combustion during biogas production, the agricultural land occupation from forest soil to arable land, would offset the positive effect of atmospheric CO2 separation by crops because of the soil CO2 emissions.

4.2.3 Midpoint impact category – Natural land occupation

Protein production

Regarding natural land transformation (Figure **41**), soybean production has the highest impact, whereas the BSF treatment facilities from all countries have a significantly lower impact on this category. The highest impact is soybean due to its agricultural production, which can transform the natural land. On the agricultural land, many fertilizers, pesticides, insecticides, or herbicides are used for better growth.

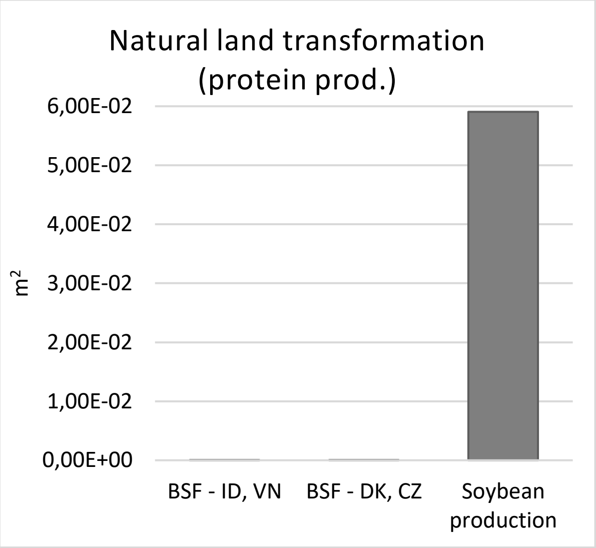


Figure 41: Natural land transformation - protein production

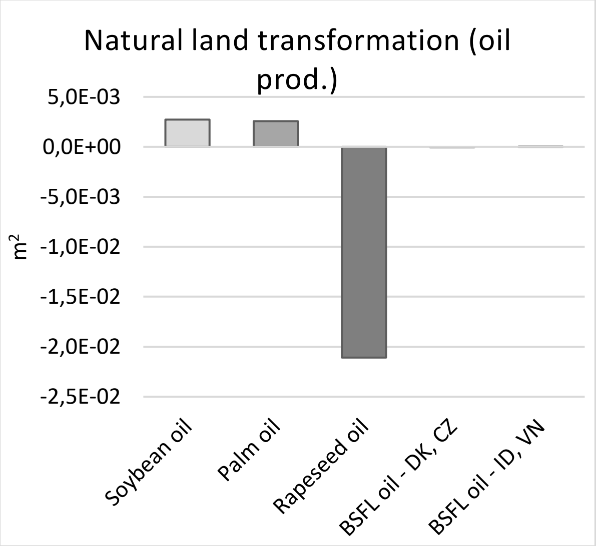


Figure 42: Natural land transformation - oil production

Oil production

Regarding natural land transformation (Figure **42**), rapeseed oil and the BSF treatment facility in Denmark and the Czech Republic have a negative impact. In contrast, soybean oil has the highest impact, followed by palm oil and the BSF treatment facility in Indonesia and Vietnam. The negative impact indicates that the rapeseed is an excellent intermediate crop or pre-crop for other plants, and its roots, which remained underground, helps to decrease the soil erosion. Rapeseed roots contain quite many nutrients that will stay in the soil when it is plowed, and that leads to enriching the organic mass in the ground.

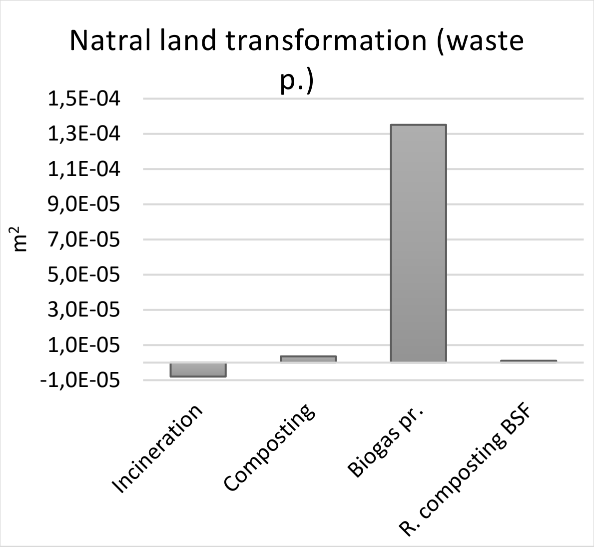


Figure 43: Natural land transformation - waste processing

Waste processing

Based on Figure **43**, the biogas production has the highest impact on natural land transformation, followed by composting and residue composting of the BSF treatment facility. In this case, the incineration process has a negative impact on this category. The negative impact indicates that this process in itself reduces waste that would otherwise end in a landfill. It is assumed that the ideal combustion during biogas production, the land transformation from forest soil to arable land, would offset the positive effect of atmospheric CO_2 separation by crops because of the soil CO_2 emissions.

4.2.4 Midpoint impact category – Human toxicity

Protein production

According to the results obtained (Figure **44**), the BSF treatment facility in Indonesia and Vietnam is the system with the highest impact on human toxicity, followed by the BSF treatment facility in Denmark and Czech Republic. The negative impact on this category is the production of soybean. The market for biowaste in Indonesia and Vietnam is the most significant contributor to this impact category in the BSF treatment facility system. A share of this impact category is also from the electricity market.

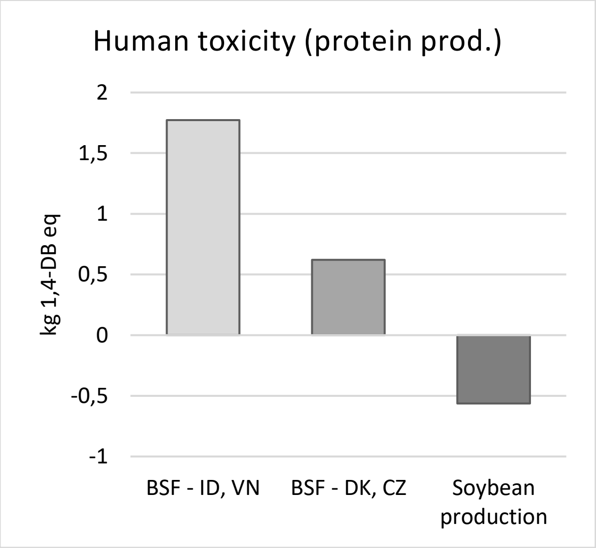


Figure 44: Human toxicity - protein production

Oil production

Based on Figure **45**, the BSFL oil in Indonesia and Vietnam is the system with the most significant impact on human toxicity, followed by rapeseed oil, BSFL oil in Denmark and the Czech Republic, and soybean oil. The market for biowaste is the main contributor to this impact category in the BSFL oil production system in Indonesia and Vietnam. Finally, the lowest impact on this category is palm oil. Nevertheless, all types of oil contribute to this impact category.

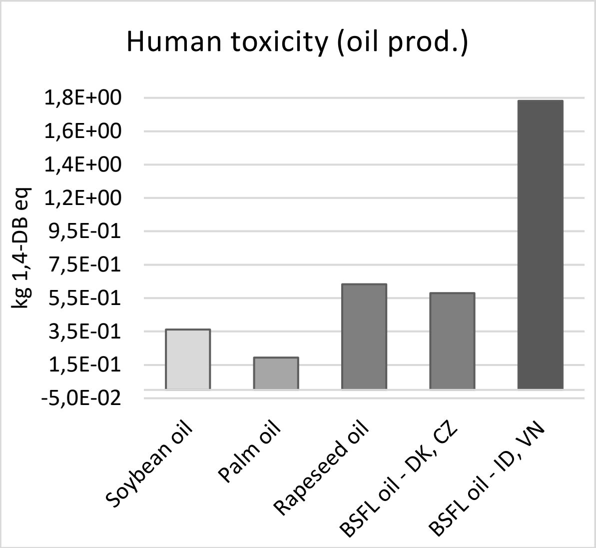


Figure 45: Human toxicity - oil production

Waste processing

Comparing the impact on human toxicity from four different processes of waste reduction (Figure **46**), it is verified that the incineration process has the highest impact on the same functional unit. The negative impact on this category is biogas production due to the biowaste treatment. The highest result from incineration indicates its high consumption of electricity and its process.

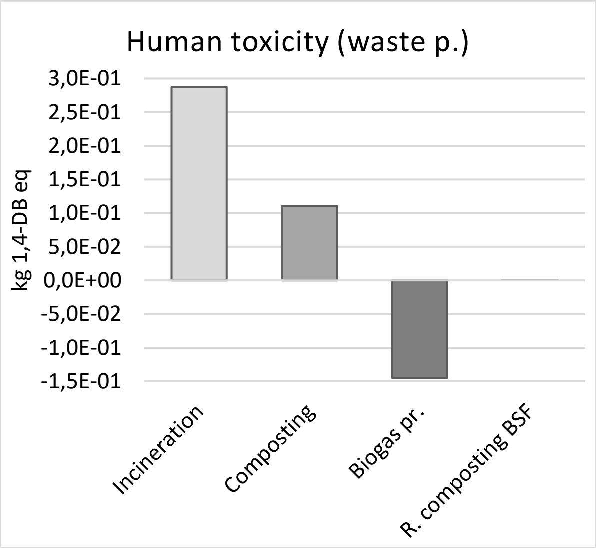


Figure 46: Human toxicity - waste processing

4.2.5 Midpoint impact category – Marine toxicity

Protein production

The BSF treatment facility in Indonesia and Vietnam have the most massive environmental impact on marine ecotoxicity (Figure **47**). In contrast, the BSF treatment facility in Denmark and the Czech Republic have a lower impact. Soybean production has a negative impact on this category. The most significant contributors to this impact are electricity consumption and the market for biowaste, which contributing to the BSF treatment facility in Indonesia and Vietnam.

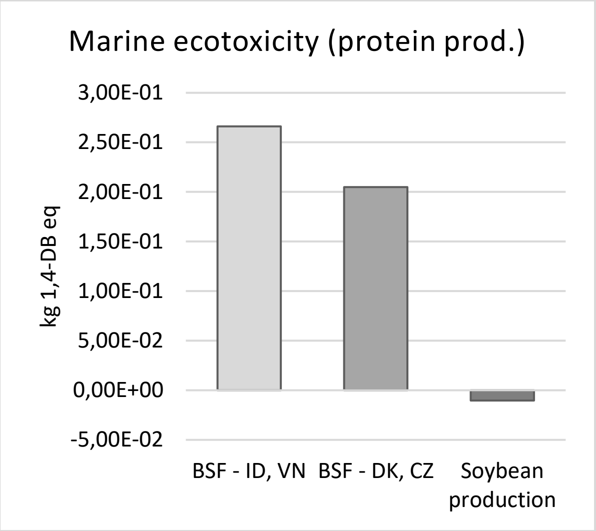


Figure 47: Marine ecotoxicity - protein production

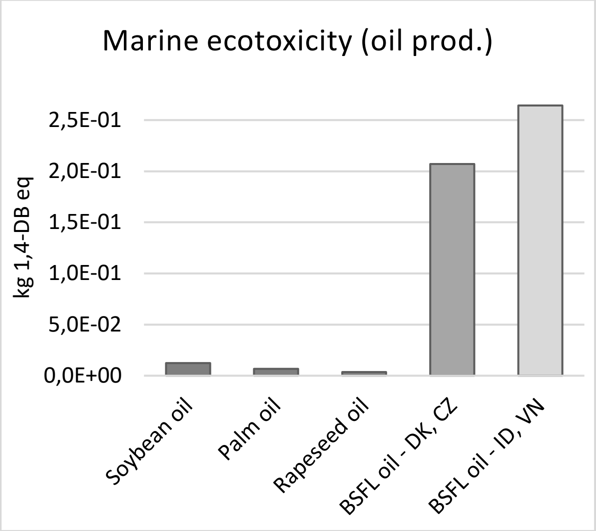


Figure 48: Marine ecotoxicity - oil production

Oil production

The BSFL oil from Indonesia and Vietnam has the most significant impact on marine ecotoxicity (Figure **48**) followed by the BSFL oil from Denmark and the Czech Republic. The lowest impact on this category is rapeseed oil. The most significant contributors to this impact are electricity consumption and the market for biowaste, which are the reason for the high impact in the BSFL oil in Indonesia and Vietnam. The electricity consumption is the main contributor as well in the BSFL oil production in Denmark and the Czech Republic.

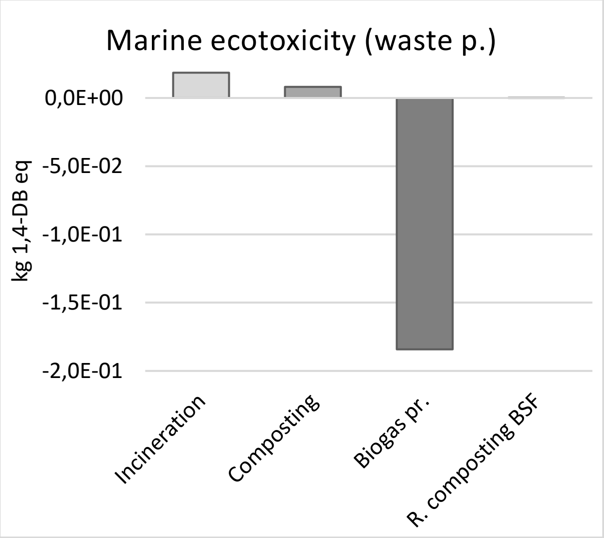


Figure 49: Marine ecotoxicity – waste processing

Waste processing

According to Figure **49**, the incineration process has the most significant impact on marine ecotoxicity. The incineration process is followed by composting and residue composting from the BSF treatment facility. The negative impact has biogas production due to its treatment of biowaste by anaerobic digestion. However, the electricity consumption and the market for biowaste are the main contributors to the incineration process.

4.2.6 Midpoint impact category – Ozone depletion

Protein production

Figure **50** shows that the BSF treatment facility in Indonesia and Vietnam has the most substantial impact on ozone depletion, followed by the facilities in Denmark and the Czech Republic. However, the market for biowaste and kraft paper is the main contributor to this impact category in the system for the BSF treatment facilities in Indonesia and Vietnam. The BSF treatment facilities in Denmark and the Czech Republic contribute to this impact category, due to the market for kraft paper used for the final packaging product. The negative impact on this category is from soybean production.

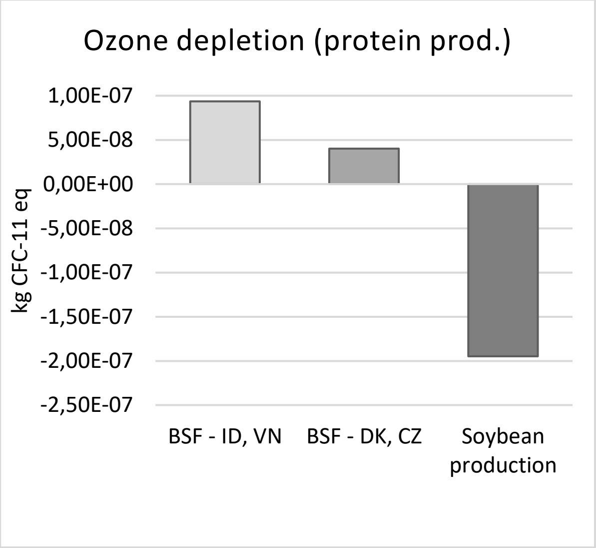


Figure 50: Ozone depletion – protein production

Oil production

Comparing the impact on ozone depletion from four different systems of oil productions (Figure **51**), it is proven that palm oil has a negative impact. The highest impact on this category is soybean oil production, followed by rapeseed oil production. The most significant contributor to this impact in itself is soybean oil production.

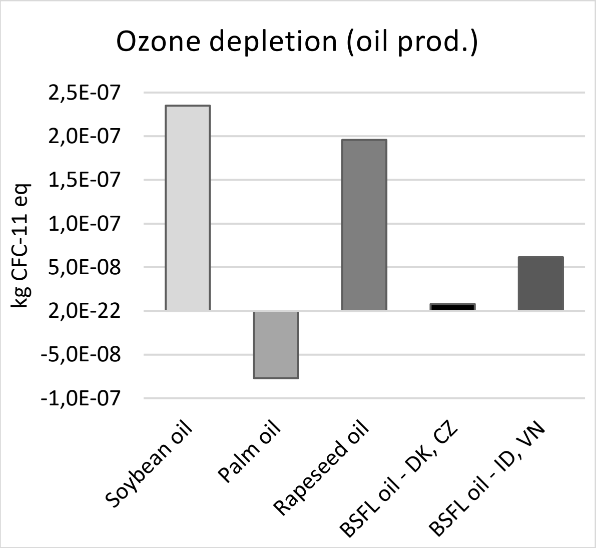


Figure 51: Ozone depletion – oil production

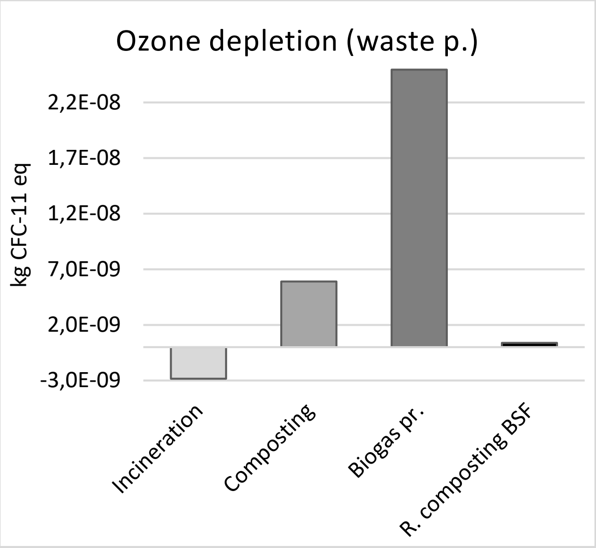


Figure 52: Ozone depletion - waste processing

Waste processing

Biogas production has the highest impact on ozone depletion, followed by the composting process (Figure **52**). The main contributors to this impact category are the treatment of biowaste through anaerobic digestion and the market for biowaste. Finally, the negative impact on this category is from the incineration process, in which the treatment of biowaste decreases emissions from the biowaste, which would not be treated.

4.2.7 Midpoint impact category – Water depletion

Protein production

Based on Figure **53**, the BSF treatment facility in Denmark and the Czech Republic have the highest impact on water depletion. In contrast, the soybean production and the BSF treatment facility in Indonesia and Vietnam have a negative impact on this category. The main contributor to this impact category is the electricity consumption at the BSF treatment facility in Denmark and the Czech Republic. The negative impact on this category is due to the reduction of biowaste at the BSF treatment facility in Indonesia and Vietnam.

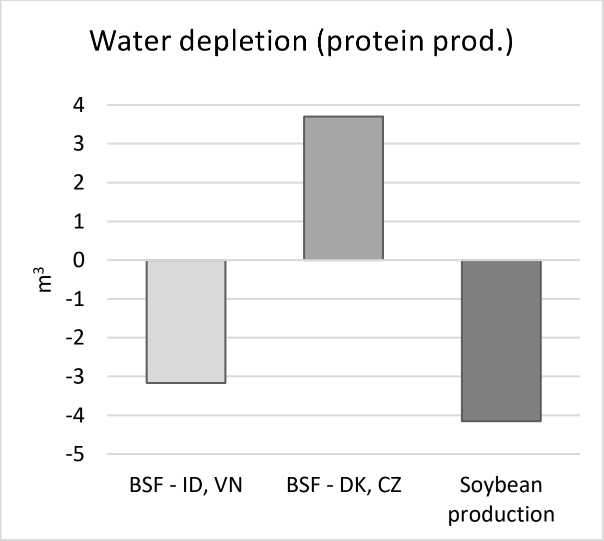


Figure 53: Water depletion - protein production

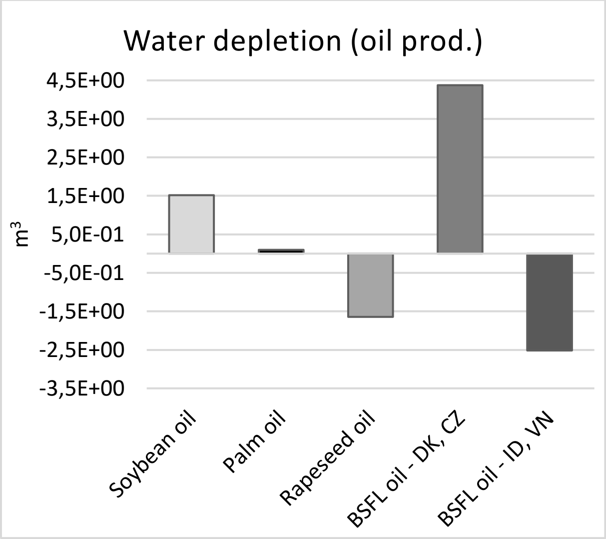


Figure 54: Water depletion - oil production

Oil production

Regarding water depletion (Figure **54**), the BSFL oil from Denmark and the Czech Republic has the most significant impact, followed by soybean oil. In contrast, the rapeseed oil and the BSFL oil from Indonesia and Vietnam have a negative impact on this category. The highest contributor to this impact category is the electricity consumption from the production of BSFL oil in Denmark and the Czech Republic. The same contributor to this impact is for the production of BSFL oil in Indonesia and Vietnam. Furthermore, the impact is then decreased by a reduction of the biowaste; thus, it makes a negative impact.

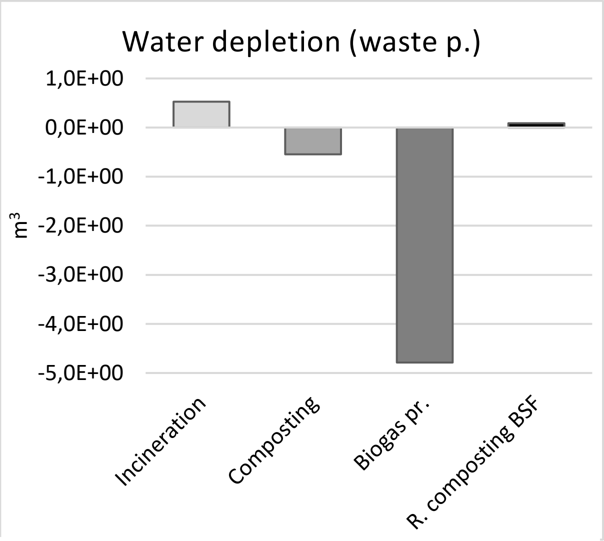


Figure 55: Waste depletion - waste processing

Waste processing

According to the results obtained (Figure **55**), the incineration process has the greatest impact on water depletion. With a significant negative impact on this category is the production of biogas. The highest contributor to this impact is from its process of incinerating, which makes it the largest one.

4.2.8 Endpoint impact category – Ecosystem

The endpoint impact categories of the ecosystem include agricultural land occupation, climate change, freshwater ecotoxicity, freshwater eutrophication, marine ecotoxicity, natural land transformation, terrestrial acidification, ecotoxicity, and urban land occupation.

Based on each comparison's results, the damage to the ecosystem diversity is represented in species per year.

Protein production

According to Figure **56**, soybean' production has the most significant impact on the ecosystem, whereas the BSF treatment facility in Denmark and the Czech Republic has the lowest impact. Soybean production has the highest impact due to the transformation from the forest shown in the results of natural land transformation. However, the market for biowaste is the most significant contributor to the BSF treatment facility in Indonesia and Vietnam.

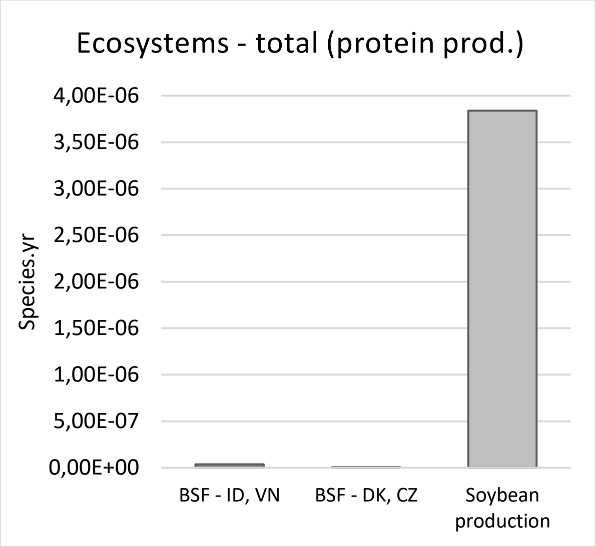


Figure 56: Ecosystem total - protein production

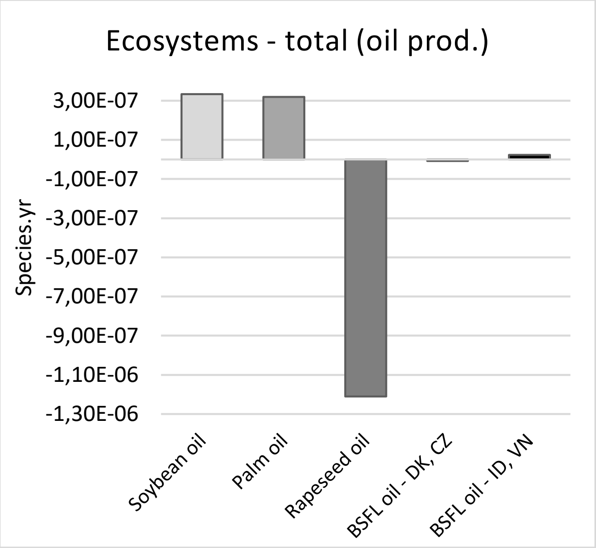


Figure 57: Ecosystem total - oil production

Oil production

Based on Figure **57**, soybean oil has the highest impact on the ecosystem, followed by palm oil. However, rapeseed oil has a negative impact due to the results of natural land transformation. The results show that the BSFL oil from Denmark and the Czech Republic has a negative impact on this category as well. Nevertheless, the BSFL oil from Indonesia and Vietnam has a significantly lower impact on this category than soybean and palm oil. Soybean oil production has the highest impact due to the transformation from the forest shown in the results of natural land transformation.

Waste processing

The damage to the ecosystem caused by oil production is represented in Figure **58**. According to the results obtained, biogas production has the highest impact on the ecosystem due to the transformation and occupation of forest areas. The results of natural land transformation are shown in Figure **43**. However, the incineration process has a significantly lowest impact on this category, followed by residue composting at the BSF treatment facility.

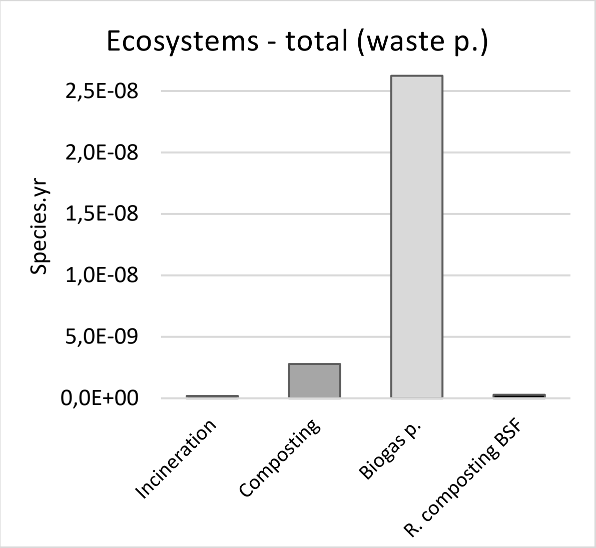


Figure 58: Ecosystem total - waste processing

4.2.9 Endpoint impact category – Human Health

The endpoint impact categories of human health include climate change, human toxicity, ionizing radiation, ozone depletion, particulate matter formation, and photochemical oxidant formation. The damages to human health for all three comparisons are presented in the unit DAILY.

Protein production

The damage to human health caused by the three different systems is represented in Figure **59**. According to the results obtained, soybean production has the highest impact on human health, followed by the BSF treatment facility in Indonesia and Vietnam. Compared to the previous alternatives mentioned, the BSF facility in Denmark and the Czech Republic have a significantly lower impact. Soybean production has the highest impact due to the transformation from the forest shown in the results of natural land transformation. The market for biowaste is the highest contributor to the BSF treatment facility in Indonesia and Vietnam.

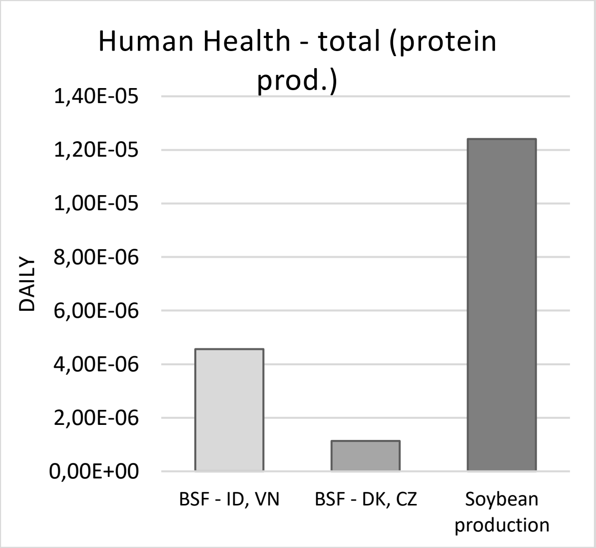


Figure 59: Human health – protein production

Oil production

Based on Figure **60**, soybean oil has the highest impact on human health, followed by palm oil and the BSFL oil in Indonesia and Vietnam. According to the results obtained, the BSFL oil in Denmark and the Czech Republic have a significantly lowest impact than the previous alternatives mentioned. The carbon dioxide from soil or biomass stock is the highest contributor to the production of soybean oil, which has such a tremendous impact on human health. However, the main contributor to the BSFL oil in Denmark and the Czech Republic is electricity consumption.

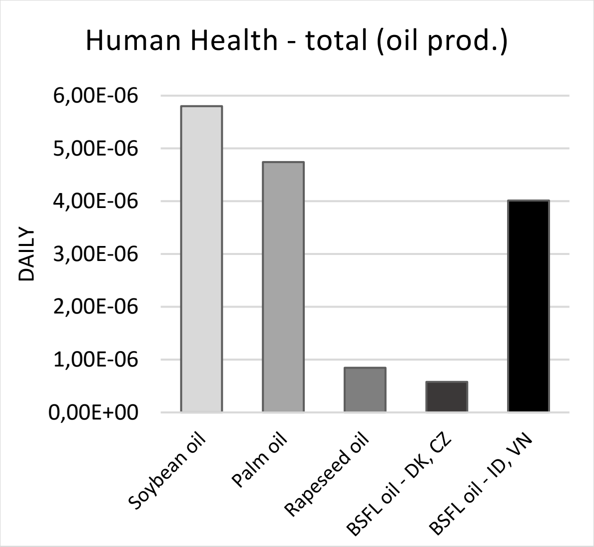


Figure 60: Human health total - oil production

Waste processing

Regarding damage to human health (Figure **61**), the production of biogas has the highest impact in this category compared to the other processes. The production of biogas is followed by the incineration process and then composting. The lowest impact in this category is residue composting from the BSF treatment facility.

The leakage of CO_2 during the biogas production shown on the results that CO_2 is the main contributor to this impact category.

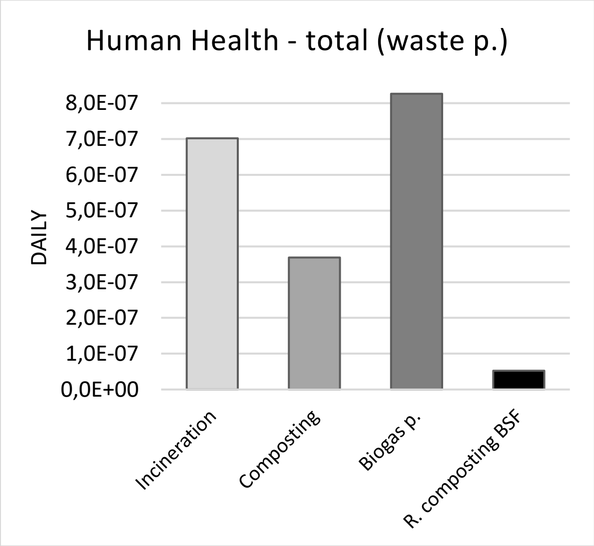


Figure 61: Human health total – waste processing

4.2.10 Endpoint impact category – Resources

The endpoint impact categories of resources include fossil depletion and metal depletion. The damages to resources for all three comparisons are presented in the unit $ (dollars).

Protein production

Finally, in Figure **62**, the damage to resources in the production of proteins, the BSF treatment in Indonesia, and Vietnam have the highest impact in this category, followed by the BSF treatment facility in Denmark and the Czech Republic. Soybean production has the lowest impact. The main contributor to the BSF treatment facility in Indonesia and Vietnam is the market for biowaste. Following the BSF treatment facility in Denmark and the Czech Republic, the main contributor is the market for kraft paper used for final packaging. However, the market for kraft paper is the main contributor to all processes.

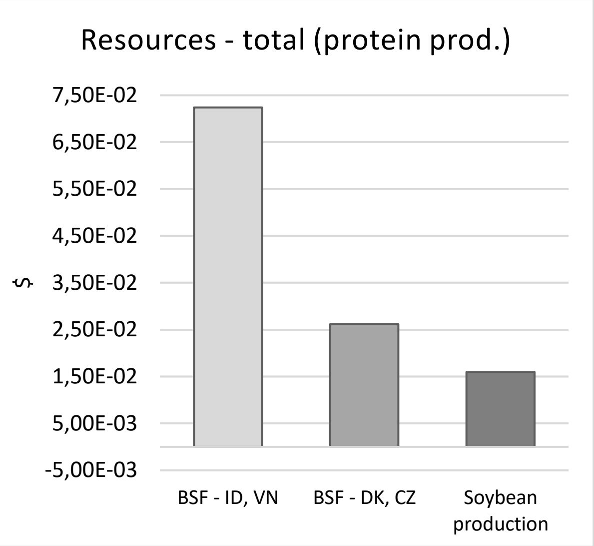


Figure 62: Resources total - protein production

Oil production

Based on Figure **63**, the most significant impact on resources is the production of rapeseed oil, followed by the BSFL oil in Indonesia and Vietnam, and then the facility in Denmark and the Czech Republic. Palm and soybean oil have a negative impact on resources. The main contributor to the production of rapeseed oil is the usage of gas and oil during production and agricultural machinery. The main contributor to the production of BSFL oil in Indonesia and Vietnam is the market for biowaste, which makes a significant impact on this category.

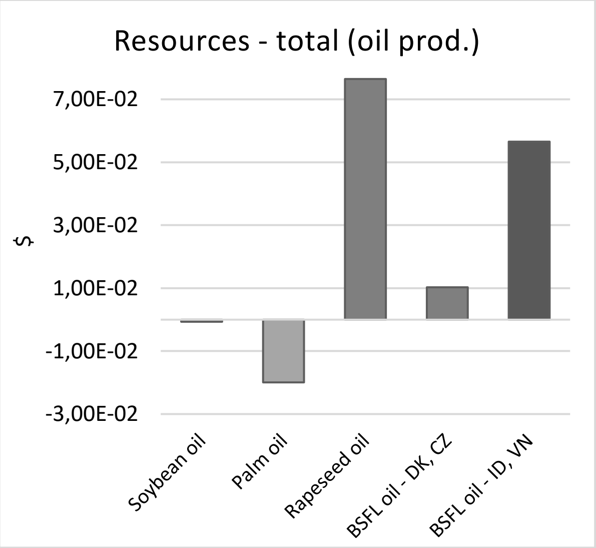


Figure 63: Resources total - oil production

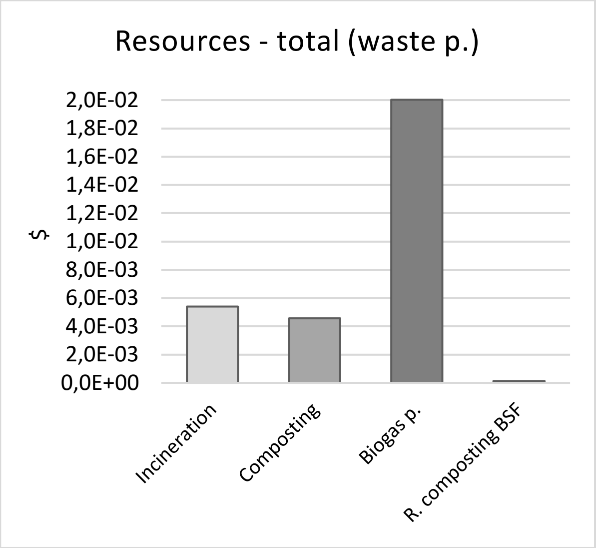


Figure 64: Resources total - waste processing

Waste processing

The production of biogas has the highest impact on damages to resources (Figure **64**) shows, followed by the incineration and composting processes. Residue composting from the BSF treatment facility has a significantly lowest impact in this category compared to the previous alternatives mentioned. The main contributor to the biogas production is its treatment of biowaste by anaerobic digestion.

4.3 LCA – Interpretation

For comparison of the environmental impacts of protein production, oil production, and waste processing, the ReCiPe method with midpoint and endpoint categories was used. Nevertheless, one must understand that LCA is never 100 % complete and precise due to some of the leaks that were not considered in the calculations.

The systems were complete and must be considered under the given circumstances. The critical draw of the conclusions and the provided recommendations on the results are based on these terms.

It is not possible to create a system that guarantees the whole LCA's full completeness, but it can be assumed that the cut-off criteria for LCA have been met.

Some of the processes of oil and protein production, or in waste processing, were not considered and included at LCA. One of the processes which are not included is the dewatering of biowaste at the BSF treatment facilities. It is assumed that the input of biowaste has perfect moisture content when arriving at the facility, so there are no further steps.

Regarding the waste pre-processing stage at the BSF treatment facility, the market for biowaste was considered only for Indonesian and Vietnamese production facilities, as the biowaste is not treated. Furthermore, the market for biowaste was not considered for Denmark and the Czech Republic, due to the utilization of biowaste. Results for the countries, with or without the market for biowaste, varies due to the different environmental impacts per country.

4.3.1 Protein production

The impact assessment results show that protein production at the BSF treatment facility in Denmark and the Czech Republic has the lowest environmental impact than the other systems. The BSF treatment facility in Denmark and the Czech Republic is the best option due to the results from damages to the ecosystem and human health. However, this treatment facility has the second-lowest impact on the damages to resources. The lowest impact obtained in this category is the production of soybean.

According to the impact assessment results, the production of protein from soybean has the highest impact on the environment. Both treatment facilities in Denmark and the Czech Republic are also packaging the final product to paper bags, increasing the environmental impact. However, the production of soybean shows higher emitted emissions from the production compared to the other systems, as seen in Figure **35** from climate change.

Based on the results in Section 1.3, soybean has to be exported to all four countries; therefore, the substitution of BSF larvae for soybean protein would make sense. Increasing soybean plantation leads to the occupation of more agricultural land, which is loaded with agricultural production, fertilizers, insecticides, herbicides, and other agricultural machinery.

If larvae were sold alive, the environmental impact would decrease due to skipping packaging, pelletizing, and storage in paper bags. The Indonesian and Vietnamese system is based on the selling larvae alive and reducing the environmental impact due to the packaging. This implementation of feeding animals by living larvae is already stated in SE Asia. However, in western Europe, the conditions for animal feeding would have to change on the farms. The BSF treatment in Indonesia and Vietnam has a more significant impact on the environment due to the market for biowaste than the facility in Denmark and the Czech Republic. Still, those facilities also reduce the biowaste, which could end up in landfills or dumpsite.

The total substitution of larvae for soybean for each country is different. According to the feeding of animals, protein-based feed is necessary for the daily lives of animals. Pigs required approximately 16 % of the protein in their feed, cattle also 16 %, and poultry needs 20 %. At 100 % of substitution, it would require 28,58 kg of biowaste to produce 1 kg of protein (2,94 kg of larvae). Table **10** shows the amount of biowaste input and larvae output per year required for animal feeding if 100 % substituted. Calculations in Table **10** are for one year of animal feeding based only on protein. After that, biowaste is taken as an input, and larvae are considered as an output as the final product. Also, the calculation is in millions of tonnes of biowaste and larvae. Table **11** shows how much food waste is generated per year in each country and how much food waste is needed to substitute 100 % of the protein in animal feed. The results from Table **11** shows that each country is not generating enough food waste to replace 100 % of the protein in animal feed.

Table 10: Substitution larvae protein for soybean protein in animal feed

[mil. tonnes/ year]	Denmark		Czech		Indonesia		Vietnam	
	biowaste	larvae	biowaste	larvae	biowaste	larvae	biowaste	larvae
Pig	53,24	5,49	6,28	0,65	34,38	3,54	117,26	12,08
Cattle	2,57	0,26	2,27	0,23	27,38	2,82	9,67	1,00
Poultry	4,16	0,43	5,28	0,54	653,49	67,34	85,18	8,78
Total	**59,97**	**6,18**	**13,84**	**1,43**	**715,25**	**73,71**	**212,11**	**21,86**

Table **11** also shows the BSFL protein substitution for each animal. The most beneficial protein substitution would be in cattle feed in each country. The most natural BSFL protein substitution would be in poultry feed, even though it is not the most beneficial, poultry can eat living larvae. In that case, BSFL protein substitution would decrease electricity consumption during the post-treatment process, especially by skipping the drying, pelletizing, and packaging. That would affect the environment due to the reduction in electricity consumption and the production of kraft paper for final packaging.

The BSFL protein substitution would decrease the occupied agricultural land for soybean. The soybean could also be used for human consumption instead.

The total results from midpoint and endpoint impact categories are within Appendix - Figure **67** and Figure **68**.

Table 11: Substitution in animal feed

	Denmark	Czech	Indonesia	Vietnam
Food waste - generated [mil. tonnes/year]	0,48	0,73	13,14	2,42
Total amount of biowaste needed for 100% substitution [mil. tonnes/year]	59,97	13,84	715,25	212,11
Percentage of substitution for pig, cattle, poultry - available with current food waste [%]	1%	5%	2%	1%
Substitution for pigs only - with current food waste [%]	1%	12%	38%	2%
Substitution for cattle only - with current food waste [%]	19%	32%	48%	25%
Substitution for poultry only - with current food waste [%]	12%	14%	2%	3%

4.3.2 Oil production

The rapeseed oil, palm oil, and soybean oil are based on the Ecoinvent 3.3 database. Only the BSF treatment facilities in Denmark, the Czech Republic, Indonesia, and Vietnam are studied in more detail.

According to the total results on damage to the ecosystem, soybean oil has the highest impact in this category, followed by palm oil. Based on the overall results of the damage on human health, the highest impact is coming from soybean production of oil, followed by palm oil. Finally, according to the total results on damage to resources, rapeseed oil production has the highest impact on this category, followed by the BSFL oil from Indonesia and Vietnam. The whole soybean oil production shows it has the most significant impact on the environment compared to the other oils. The best option for oil production is rapeseed oil or BSFL oil. The results show that the oil of BSFL in Denmark and the Czech Republic has a potential due to the lower environmental impact compared to other oils.

Based on the results, the BSFL oil produced in Indonesia and Vietnam has a high impact on human health due to the market for biowaste, which increases the impact and reduces the biowaste. However, the BSFL oil in each country showed that the impact on the environment is not that high compared to the soybean oil or the other oil variations. The total results from midpoint and endpoint impact categories are within Appendix - Figure **65** and Figure **66**.

4.3.3 Waste processing

The biogas production, composting, and incineration process are based on the Ecoinvent 3.3 database. Therefore, only residue composting at the BSF treatment facility is studied in more thorough.

According to the total results of the impact assessment, the production of biogas has the most significant impact compared to the other waste processes. Based on the results from residue composting in the BSF treatment facility, the input of biowaste is not considered from the market for biowaste. However, it is considered from the production of the BSF treatment facility.

Based on the results, the residue composting form BSF treatment facility showed that the impact on the environment is lowest than the other waste processes. The total results from midpoint and endpoint impact categories are within Appendix - Figure **69** and Figure **70**.

5 Discussion

No food or product will always be a sustainable or non-sustainable option. Things that we buy are related to the way that they are produced, processed, and transported. However, there is no product that would be sustainable. Everything that we consume has an environmental footprint, and it is our obligation to think about what is best for the human population and the environment.

Direct carbon dioxide emissions from larvae were not included in the calculations at openLCA at the rearing and harvesting process of the proposed systems the BSF treatment facilities. The direct emissions might have affected the results, but not more significant than the environmental impact from soybean feed or oil production.

As it was already mentioned in interpretation, LCA is never 100 % complete and precise due to the leaks that were not considered in the calculations. It is not possible to 100 % relay on the results due to the leaks in the database. Only the proposed system of the BSF treatment facility in Denmark, the Czech Republic, Indonesia, and Vietnam was more detailed studied. The rest of the systems were taken from the Ecoinvent 3.3 database. Therefore, the leaks can be in those systems which did not include everything. However, each system can work differently due to the different adaptability in each county.

According to the comparison of waste processing, all systems are based on the Ecoinvent 3.3 database. Therefore, only residue composting of the BSF treatment facility is more detailed studied. However, the residue composting is considered as a regular composting facility. The comparison of waste processing is not based on local conditions of four countries but is considered as an average process.

The results showed that the BSF treatment facilities for protein, oil, and residue composting has a significantly lower impact on the environment than other systems. Although, the results of the BSF treatment facility in Indonesia and Vietnam showed that the highest contributor is from the market for biowaste, which reduces the biowaste compared to the other systems based on oil or protein production. Thus, the proposed systems of the BSF treatment facilities are more beneficial, especially by the reduction of biowaste.

According to waste management, Denmark set a goal that 50 % of household waste will be recycled, including biowaste, by 2022. Therefore, a BSF treatment facility in Denmark is suitable due to the input of treated biowaste and overall results from impact assessment. The BSF treatment facility in Denmark would be a unique start-up for its production of protein-based animal feed.

Based on the results from oil production, the BSFL oil has quite positive results compared to other oil productions. This could also be an alternative and excellent compensation for rapeseed oil. Denmark does not produce soybean on its land, and it is imported mainly from Argentina and Brazil. In this case, emissions from transporting can be reduced due to substituting soybean protein for the BSFL protein.

The BSF treatment facility is based on similar conditions and waste management in Denmark and the Czech Republic. According to Czech waste management, the recycling rate is lower than the Danish one; therefore, the development of the recycling rate is increasing. Recycling includes the biowaste is still not implemented in the Czech household waste management. With implementing a new sorting system for organic waste into households, the potential for the development of the BSF treatment facility would be even more beneficial than before. Therefore, the current development of the BSF treatment facility in the Czech Republic would also be a great option based on impact assessment results.

Indonesian and Vietnamese waste management is still inferior; however, these countries have set a goal by increasing the recycling rate. Currently, Indonesia and Vietnam do not have a sorting system for organic waste or other waste. Waste management is impoverished in those countries. Although, the whole system of the BSF treatment facility is based on the current working facility placed in Indonesia, which uses the biowaste input from the fruit and vegetable market. Currently, mostly all biowaste ends up in landfills and has enormous environmental consequences. With an increasing sorting system, especially for biowaste, the development of the BSF treatment facility would be significantly more beneficial. The BSF treatment facility could help those countries to reduce biowaste by larvae, plus the benefits such as the production of larvae protein and oil. Furthermore, another significant advantage for those countries is the production of organic fertilizers, which could also be beneficial for agricultural land.

The larvae substitution for soybean protein at animal feed will be different in each country. The development of the BSF treatment facilities in each country can be different due to their financial support and environmental conditions.

Based on the results from Section 1.3, soybean production has been declining in recent years due to low yields; thus, farmers switch to more profitable crops. Instead of using soybean as animal feed, it can be used for human consumption. An example could be used for people on a special diet or a vegetarian diet. Even though the occupied agricultural land would not decrease, the overall climate impact would decrease, due to people eating soybean-based food, instead of poultry, cattle, and pigs. The emission from the poultry, cattle, and pigs, could be decreased if people would eat soybean-based food instead of meat from animals.

Currently, 29 % of Denmark's primary energy sources, comes from renewable energy. However, Denmark has a goal to be fossil-free by 2050. Denmark has the highest potential for implementing the BSF treatment facility. With increasing electricity consumption from renewable energy, the impact on the environment would decrease. Therefore, the development of the BSF treatment facility in Denmark would be more beneficial than before.

With the current Czech production of renewable energy, the BSF treatment facility would use mostly electricity from fossil fuels. This is not the best option for the environment; however, the Czech Government has the vision to rapidly increase the production of renewable energy. Thus, the development of the BSF treatment facility in the Czech Republic would be more beneficial than before.

Indonesian and Vietnamese current energy consumption is based on fossil fuels, which makes a significant impact on the environment. Although, those two countries have a goal to reduce fossil fuel consumption and increase the source of renewable energy by 2025.

On the other hand, Indonesia and Vietnam have great potential to use solar panels due to their local climate conditions. Vietnamese energy production has a high potential to use renewable energy from hydropower plants and supply electricity to the BSF treatment facility.

The other option could be developing renewable energy sources such as photovoltaic panels, solar panels, and heat pumps, which would be a part of the facility. Renewable energy could produce heat and electricity, which is needed for the facility to run. Therefore, the BSF treatment facility would have the possibility to run on 100 % renewable energy, which would be more beneficial for the environment.

6 Conclusion

This project aims to assess the environmental impacts associated with the production of protein, oil, and the reduction of biowaste. The systems of protein and oil production are based on the local conditions in Denmark, the Czech Republic, Indonesia, and Vietnam. The systems of waste processing are based on regular conditions and are not based on local conditions in each country.

Based on the final results, the BSF treatment facilities showed a lower environmental impact than soybean production, both in oil and protein production. However, protein production in the BSF treatment facility has the highest impact on ozone depletion, due to the high electricity consumption and the market for biowaste. The system for soybean protein production is based on the Ecoinvent 3.3 database, and the results show that it has a negative impact on ozone depletion. However, in oil production, the most significant impact on ozone depletion has soybean production, and the BSF treatment facilities in each country have a significantly lower impact on this category.

According to the marine ecotoxicity, the protein and oil production at the BSF treatment facility in Denmark, the Czech Republic, Indonesia, and Vietnam, have the highest impact on this category, due to the electricity consumption and market for biowaste.

Based on the impact assessment results, the production of biogas shows the highest impact on the environment in comparison with other mentioned systems. The residue composting from the BSF treatment facility has better results when compared to the composting facilities. The results from the residue composting at the BSF treatment facility show an average CH_4 production of 0,63 g and N_2O production of 0,06 g per 1 kg of biowaste treated. The results were compared with GHG emissions from regular composting, as described in Section 4.2.1, in the midpoint impact categories to climate change. The BSF's direct emissions are closely linked with feedstock characteristics and treatment parameters, such as the ratio of larvae and amount of biowaste. The comparison of residue composting at BSF treatment facility versus composting, regarding direct GHG emissions, highlights the potential of BSF treatment facility as a low GHG emissions option.

Regarding the total results of the impact assessment, the production of soybean oil has the highest impact on the environment in comparison to the other oils. The results also show that the BSFL oil has the lowest kcal per 1 kg of oil compared to other oils; thus, it could be a healthier option in the food industry. The production of BSFL oil has potential at substitution for other oil in all four countries due to the impact assessment results.

The BSF larvae are rich in protein and fat, and it is proper compensation for the production of oil and animal feed. From the endpoint impact categories of the ecosystem, human health, and resources, it is evident that the BSF treatment facility is a better option for producing protein-based animal feed in all four countries.

When considering the indirect emissions, it is the electricity consumption for the BSF treatment facility that plays a significant role. It is considered that there is a direct electricity consumption of 11,58 kWh for BSF treatment facilities in Denmark and the Czech Republic when producing protein. In Indonesia and Vietnam, electricity consumption is 10,6 kWh during the production of protein. The direct electricity consumption in Denmark and the Czech Republic is 11,89 kWh for BSF treatment facility when producing oil. In Indonesia and Vietnam, direct electricity consumption is 10,9 kWh when producing oil. Finally, the direct electricity consumption of 5,6E-04 kWh is used for composting at the BSF treatment facility.

The rearing and treatment phase in the BSF treatment are those that consume most of the electricity. The increase in electricity consumption with the current system can affect the overall GWP. However, the increase in electricity consumption would be from equipment that was not considered in the calculation at openLCA, such as drying sieve at harvesting process or dewatering machine at waste pre-processing. With such equipment, it is estimated that electricity consumption will increase. However, this factor is strongly influenced by the energy source in each country.

Finally, the evaluating and quantifying avoided emissions from the BSF treatment facilities depends on emissions from the products which are substituted. Furthermore, it depends on the products from the BSF treatment facility that are requested and accepted in the market. In this study, larvae meal is considered an ideal substitute for soybean meal for animal feed. Furthermore, BSFL oil is considered a good substitution for oils such as rapeseed oil, palm oil, and soybean oil.

It is known that the characteristics of the biowaste fed to the larvae, influences the larvae yield, as well as the content of larvae protein. The biowaste can decrease or increase the quality parameters of the larvae meal obtained.

Nevertheless, in all countries, the BSF treatment facility reduces a big part of household waste, unlike soybean oil and soybean protein productions. Another benefit of the BSF treatment facilities is producing organic fertilizer, which can be used on agricultural land with lower emissions than regular composting facilities.

This research aimed to identify effective solutions at protein production, oil production, and waste processing. The results showed that the most beneficial and effective solution for protein production would be the development of the BSF treatment facility in Denmark and the Czech Republic. The development of the BSF treatment facility in Indonesia and Vietnam must improve their sorting system for waste management to utilize the biowaste for the production of protein-based larvae meal. However, the development of the BSF treatment facility in Indonesia and Vietnam is still beneficial, even without proper waste management. Further recommendation for the protein production, would be to substitute the soybean protein with BSF larvae protein in the animal feed for poultry and cattle in each of the four countries. The BSFL could be sold living for poultry feed, and pelletized BSFL could be sold for cattle feed. The BSF protein cannot be implemented for a 100 % substitution due to insufficient biowaste generated from the households. Therefore, the replacement can be partly split between poultry and cattle protein-based feed.

According to oil production, the results showed that it is possible to use BSFL oil as a substitute for other oils produced in each country.

The possibility to substitute the BSFL oil with other oils in everyday household usage is possible. However, the taste has not been taken into consideration, but the BSFL oil is lower in kcal from the nutrition point of view. Usage in the food industry would also be a possibility to replace some of the oils currently used, like palm oil and soybean oil, which is both have a high impact on the environment.

Based on the comparison of waste processing, biogas production showed the highest impact on the environment. The residue composting at the BSF treatment facility still showed the best results.

In waste processing, it is recommended to use wet biomass, such as organic waste from households, to produce BSFL protein and oil. The recommendation would still be to use organic waste from agriculture and dry biomass to produce biogas. The disposal of the BSF treatment facility's biowaste would go to the residue composting, which produces organic fertilizer for agricultural land.

If the whole world wants to have a greener future and archive the goals for 2050, such as decreasing GHG emissions or fossil fuels, it is necessary to start right away. Even though it is not possible to archive 100 % of substitution, it is still better to substitute something than nothing. The development of the BSF treatment facility can give us the possibility to make changes in the world and move us to an eco-friendlier world.

The study proves that Denmark is the best for developing the BSF facility out of the four countries. Therefore, starting in Denmark, which has a strong economy and the possibility to develop the BSF treatment facility, could make an even greener and eco-friendlier country. Denmark is the best starter due to their better waste management, and sorting system in the households. The Danish renewable energy is high, so the facility can run on 100 % renewable energy and decrease the emissions from fossil fuels. The Czech Republic is still recovering its economy and waste management, so the development of the facility would be a bit harder than in Denmark. Indonesia and Vietnam have the poorest economy with waste management than other countries in this study. However, the development of the facility has the potential to use renewable energy, especially from hydropower plants and increase their waste management.

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8. Appendix

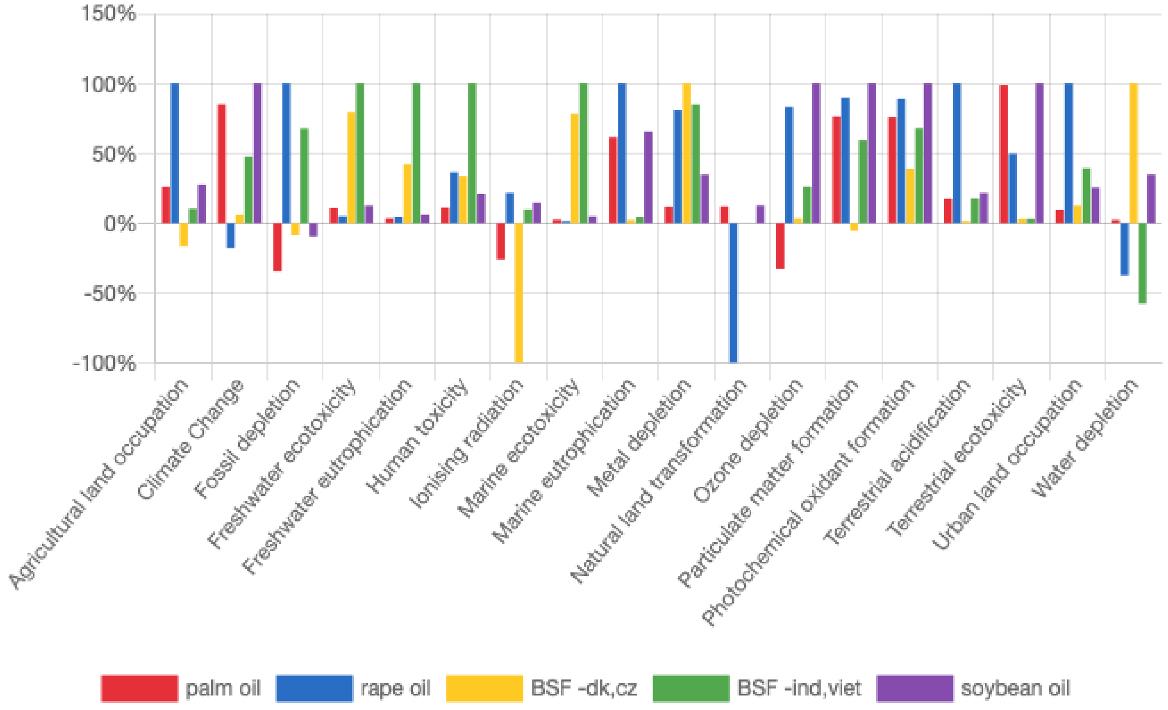

Figure 65: Appendix - Midpoint impact categories – oil production

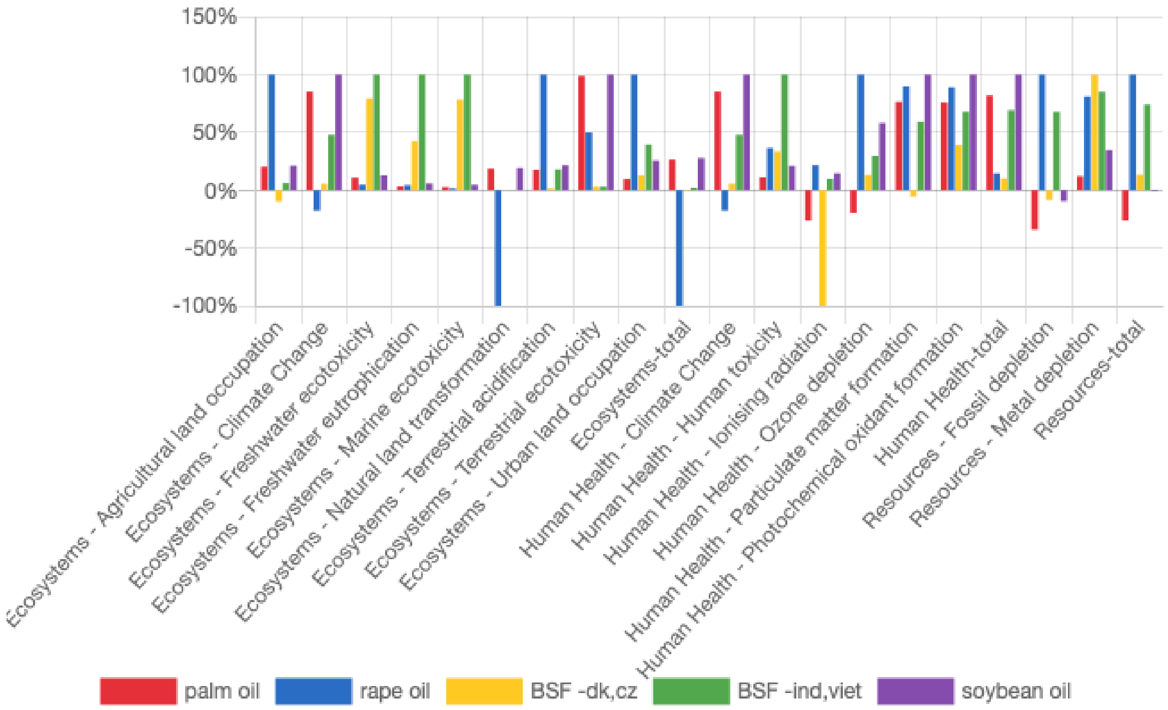

Figure 66: Appendix - Endpoint impact categories – oil production

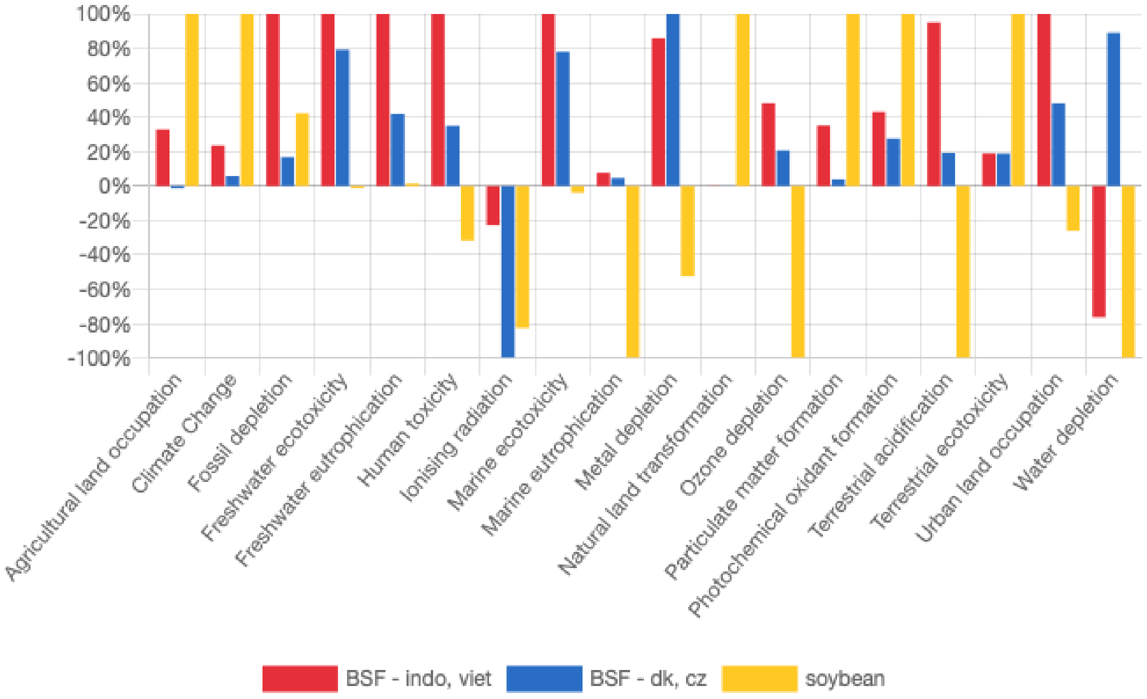

Figure 67: Appendix - Midpoint impact categories – protein production

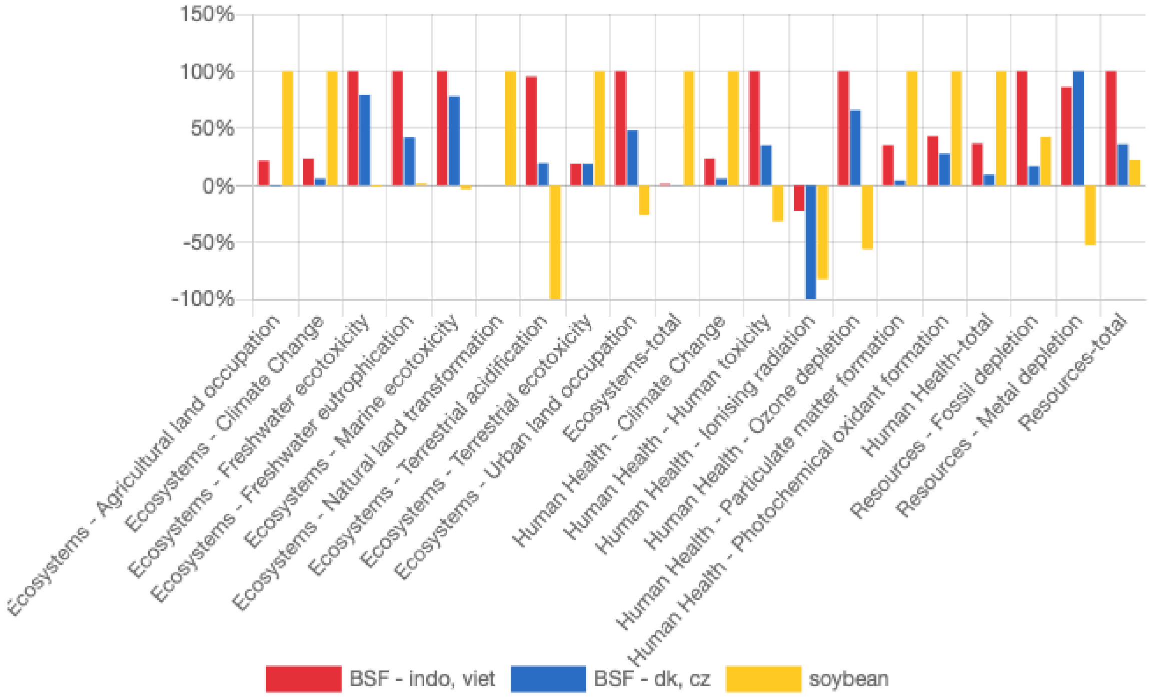

Figure 68: Appendix - Endpoint impact categories – protein production

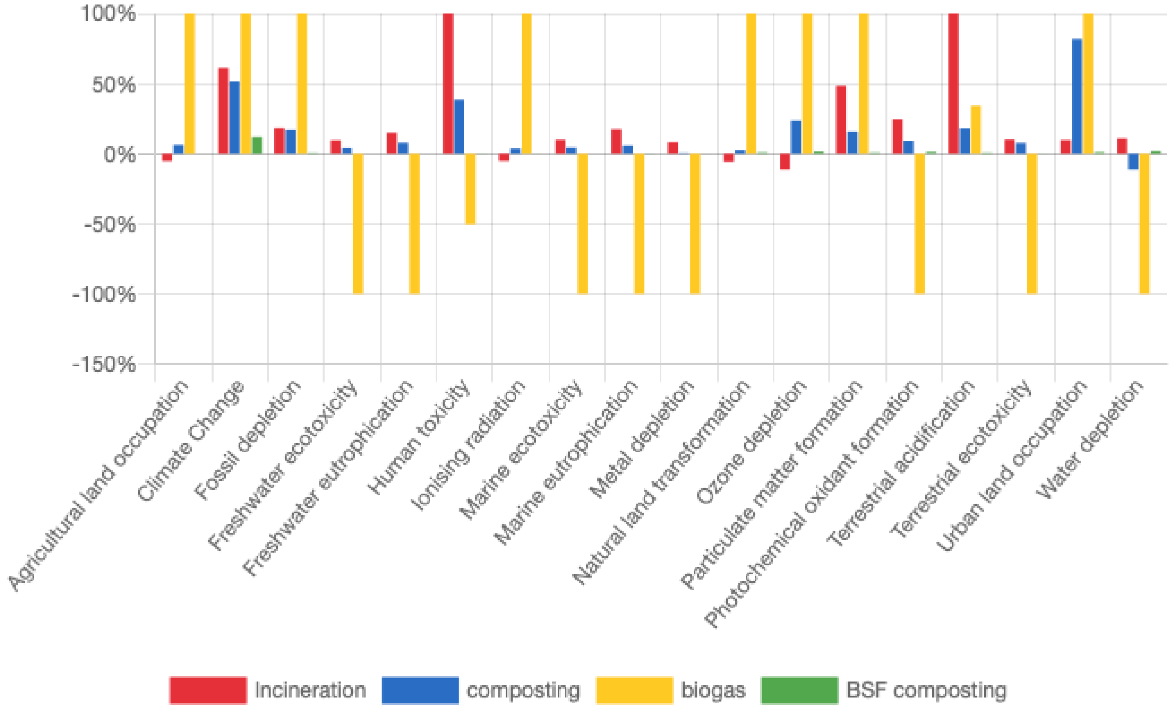

Figure 69: Appendix - Midpoint impact categories – waste processing

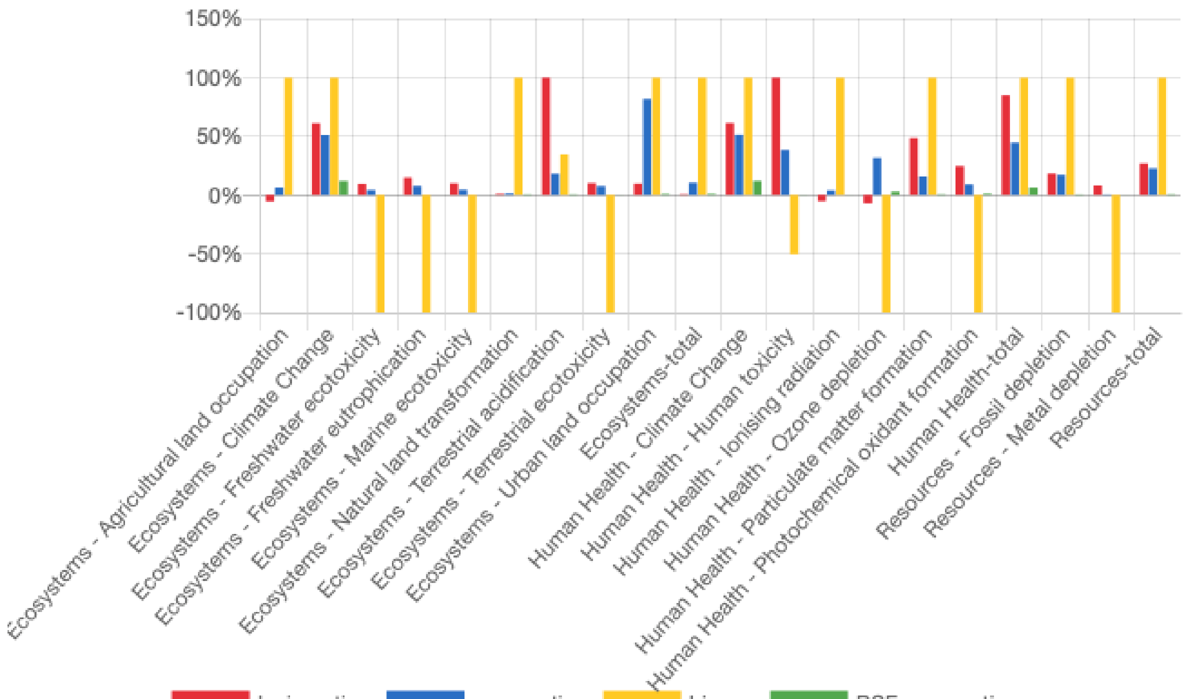

Figure 70: Appendix - Endpoint impact categories – waste processing

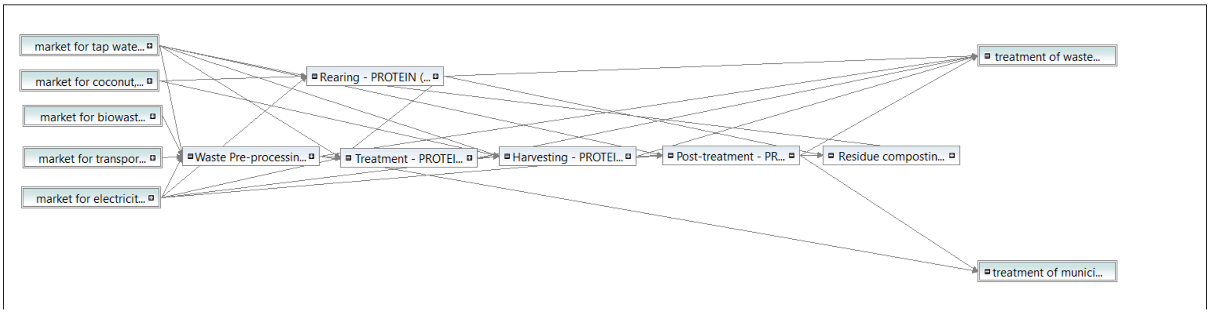

Figure 71: Appendix - The BSF facility - protein production

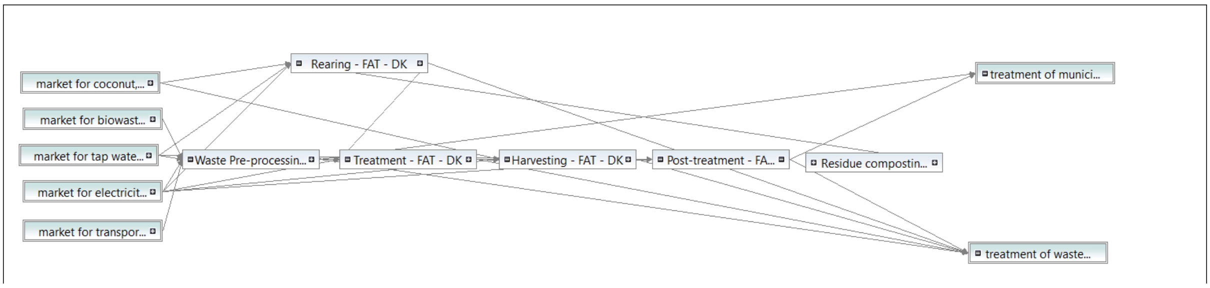

Figure 72: Appendix - The BSF facility - oil production