Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Elise Bellmann

Life cycle assessment of fish sludge utilization for black soldier fly substrate

Master's thesis in Energy and environmental engineering
Supervisor: Juudit Ottelin
June 2023

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Preface

This thesis is written in the spring of 2023 at the Norwegian university of science and technology (NTNU), as the final assignment of the energy and environmental engineering study. The thesis belongs in the energy and environmental analysis profile of the 5-year study program, and is delivered to the faculty of engineering science (IV) and the department of energy and process engineering (EPT). 30 credits are the size of this thesis. Pronofa has contributed to this thesis, and Eva Marit Hystad Byhrø have been the contact.

I would like to thank Juudit Ottelin at NTNU and Eva Marit Hystad Byhrø from Pronofa for the cooperation. I appreciate the guidance and help they have given me.

Norwegian university of science and technology (NTNU)

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Summary

As the world's population grows, and the demand for feed increases, could black soldier fly be an important protein source with low environmental impact. Breeding black soldier flies requires a large amount of substrate to make the larvae grow. A number of factors, like environmental impact and quantity, must be considered while choosing the larvae substrate. Using waste sources is preferred, as waste has low environmental impact, and the utilization for black soldier fly could solve waste problems. A potential waste source could be fish sludge from breeding facilities, because the utilization will prevent nutrition emissions to the environment. However, other utilization options for fish sludge could have a better environmental performance than black soldier fly substrate, and the environmental impact could potentially change as the sludge is transported wet or dry.

Previous LCA studies have assessed sludge utilization options like bioenergy and fertilizer production, or the impact from not utilizing fish sludge [1–4]. LCAs on black soldier flies have included different substrate options, but never fish sludge [5–7]. In addition have no studies included transportation options for wet and dry sludge [8]. The aim of this study is therefore to calculate and compare the ecosystem impact from utilizing fish sludge for black soldier fly, bioenergy, and fertilizer, compared to not utilizing the sludge in a scenario analysis.

The impact from each utilization scenario were calculated in an LCA with respect to the eutrophication and global warming potential for 20 years. The main phases for the sludge's lifetime were dewatering and drying, transportation of sludge, and utilization specific processing. These phases required manufacturing of machinery (A1-A3), transportation (A4-A5), maintenance (B2-B4), operation (B1 and B6), and recycling (C1-C4). Scenarios with dried sludge required more machinery, but less transportation. Also, alternative impacts were substitutes with two methods, as the sludge would prevent potential ecosystem impact by replacing products. The first substitution method substituted impact related to which product the sludge would replace, while the second method substituted the base case impact from not utilizing the sludge.

The results show that utilization for black soldier fly has the lowest environmental impact compared to other utilization scenarios. The alternative utilization scenarios used fish sludge for biogas and fertilizer production, and a base case where sludge was not utilized was included as well. The base case had the largest environmental impact, with $7.65*10^{-4}$ species per year, because of the large phosphorus emissions. After substituting avoided emissions from the utilization scenarios with two different methods became the ecosystem impact negative for scenarios where fish sludge was used for black soldier fly.

Drying machinery at the breeding facilities had significant ecosystem impact, which made the impact from drying larger than the extra emissions from transporting sludge wet. This made the scenario where fish sludge was transported wet for black soldier fly substrate the preferred option. However, when the materials were assumed to be recycled, the impact from drying decreased. Recycling made the dry and wet transportation scenario equally preferred for black solder fly utilization. This shows how sensitive the results are

to changes in drying machinery, which implies that the main effort should be to lower drying impacts. To conclude, the results show how using fish sludge as black soldier fly is a reasonable choice in an environmental perspective compared to other utilization options.

The recommendation after interpreting the results is to build the dewatering and drying machinery with the intention to reduce the ecosystem impact from this phase. An impact reduction could be done by down scaling the machinery, sharing heavy drying machinery between multiple facilities, and recycle most materials. Even without these measures will the utilization scenarios have lower ecosystem impact then the base case. This makes utilization scenarios preferred, especially utilization for black soldier fly substrate seems like a good utilization option.

Sammendrag

Etter hvert som verdens befolkning vokser, og etterspørselen etter fôr øker, kan svart soldatflue være en viktig proteinkilde med lavt miljøavtrykk. Produksjonen av svarte soldatfluer krever en stor mengde substrat for å få larvene til å vokse. En rekke faktorer, som miljøpåvirkning og mengde, må vurderes ved valg av larvesubstrat. Bruk av avfallskilder er foretrukket, da avfall har lav miljøpåvirkning, og utnyttelse for svart soldatflue kan løse avfallsproblemer. En mulig avfallskilde kan være fiskeslam fra oppdrettsanlegg, da utnyttelsen vil hindre utslipp av næringsstoffer til miljøet rundt. Andre bruksområder for fiskeslam kan være mer bærekraftig enn svart soldatfluesubstrat, og miljøpåvirkningen kan muligens endres etter hvert som slammet transporteres vått eller tørt.

Tidligere LCA-studier for slamutnyttelse har vurdert bioenergi og gjødselproduksjon som mulige bruksområder, eller miljøvtrykket av å ikke utnytte fiskeslam [1–4]. Livssyklusanalyser på svarte soldatfluer har inkludert forskjellige substratalternativer, men aldri fiskeslam [5–7]. I tillegg har ingen studier inkludert transportalternativer for vått og tørt slam [8]. Målet med denne studien er derfor å beregne og sammenligne økosystempåvirkningen fra bruken av fiskeslam til svartsoldatflue, bioenergi og gjødsel, sammenlignet med å ikke utnyttelse slammet i en scenarioanalyse.

Effekten fra hvert utnyttelsesscenario ble beregnet i en LCA med hensyn på eutrofiering og globalt oppvarmingspotensial over 20 år. Hovedfasene for slammets levetid var avvanning og tørking, transport av slam og bruksspesifikk behandling. Disse fasene krevde produksjon av maskineri (A1-A3), transport (A4-A5), vedlikehold (B2-B4), drift (B1 og B6) og resirkulering (C1-C4). Scenarier med tørket slam krevde mer maskineri, men mindre transport. Alternative miljøpåvirkninger var også substituert med to metoder, da slammet ville forhindre mulig økosystempåvirkning ved å erstatte produkter. Den første substitusjonsmetoden substituerte miljøpåvirkning knyttet til hvilket produkt slammet ville erstatte, mens den andre metoden substituerte miljøpåvirkningen fra grunntilfellet der slammet ikke ble utnyttet.

Resultatene viser at utnyttelse for svart soldatflue har lavest miljøpåvirkning sammenlignet med andre utnyttelsesscenarier. De alternative utnyttelsesscenarioene benyttet fiskeslam til biogass- og gjødselproduksjon, og et basistilfelle hvor slam ikke ble utnyttet ble også inkludert. Grunntilfellet hadde den største miljøpåvirkningen, med $7,65 * 10^{-4}$ arter per år, på grunn av de store fosforutslippene. Etter substitusjonen ble økosystempåvirkningen negativ for scenarier der fiskeslam ble brukt til svart soldatflue, med begge substitusjonsmetodene.

Tørkemaskineri ved oppdrettsanleggene hadde betydelig økosystempåvirkning, noe som gjorde påvirkningen fra tørking større enn de ekstra utslippene fra transport av vått slam. Dette gjorde scenariet der fiskeslam ble transportert vått for svart soldatfluesubstrat til det foretrukne alternativet. Men når materialene ble antatt å bli resirkulert, ble miljøpåvirkningen fra tørking redusert. Resirkulering gjorde tørt og vått transportscenario like foretrukket for bruk av svart soldatflue. Dette viser hvor følsomme resultatene er for endringer i tørkemaskineriet, noe som innebærer at hovedinnsatsen bør være å

redusere miljøpåvirkningen herifra. For å konkludere viser resultatene hvordan bruk av fiskeslam som svart soldatflue substrat er et rimelig valg i et miljøperspektiv sammenlignet med andre utnyttelsesmuligheter.

Anbefalingen etter tolkning av resultatene er å bygge avvannings- og tørkemaskineriet med den hensikt å redusere miljøpåvirkningen fra denne fasen. Miljøavtrykket kan reduseres ved å nedskalere maskineriet, dele tungt tørkemaskineri mellom flere anlegg og resirkulere de fleste materialer. Selv uten disse tiltakene vil utnyttelsesscenarioene ha lavere økosystempåvirkning enn basistilfellet. Dette gjør bruksscenarier å foretrekke, spesielt bruk for svart soldatfluesubstrat virker som et godt utnyttelsesalternativ.

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Abbreviations

LCA= Life cycle assessment

LCIA= Life cycle impact assessment

BSF= Black soldier fly

BSFL=Black soldier fly larvae

GHG=Greenhouse gas

GWP= Global warming potential

EP= Eutrophication potential

kWh= Kilo Watt hour

EPD= Environmental Product Declaration

RAS=Recirculating aquaculture system

SHS= Superheated steam

Zn=Zinc

Cd= Cadmium

P= Phosphorus

N= Nitrogen

CF= Characterization factor

m= Meter

1 Introduction

Problems surrounding the future food supply have sparked an interest in the research community and business world. As the population grows, the food demand will grow, which requires new and smarter food production. The second sustainability goal enlightens how smarter resource use could be a crucial factor when counteracting hunger [9]. The goal aims to develop sustainable agriculture and modern technologies, together with more fair distribution of resources. Using insects for animal feed could be a step closer to achieving this sustainability goal. Insects have the right nutrition value for indirect and direct human consumption and could provide a sustainable type of farming [10]. Black soldier fly (BSF) is one of the insect species that can be used as a protein source for livestock.

Black soldier farming will require substrate for the larvae to grow. To achieve a sustainable BSF farming, and a circular economy, the substrate should be a waste product from another process. Fish sludge is usually treated as waste, but could potential be used as BSF substrate. When fish sludge is treated in fish breeding facilities, a promising source will not be utilized, and the sludge's high phosphorus and nitrogen content could have a negative impact on the environment. Therefore, it will be important to find more sustainable alternatives for fish sludge utilization.

Pronofa is planning to establish a new black soldier fly factory in Moss, Norway, with a yearly production at 50.000 tons black soldier fly larvae (BSFL) [11]. Such large production will require a substrate source that is large and constant during the entire year. Putting today's EU regulations for animal feed aside, fish sludge could be a promising substrate [12–14]. It would therefore be interesting to assess whether fish sludge as BSF substrate is a sustainable choice. Previous LCA studies, like Seng Liew, Beyers or Ferronanto and colleagues, have done research on the production of BSF with different substrates [5–7]. However, they have not assessed the use of fish sludge as a substrate, and the studies focused on the flies as the final product. Cristiano and colleagues have done a comparative LCA with different scenarios for fish sludge utilization, but BSF substrate was not one of these scenarios [8]. This study will combine parts of the LCAs on black soldier fly with Cristiano's study, to assess the sustainability of fish sludge utilization in BSF production compared to other common utilization. This provides the research question:

What is the environmental impact of utilizing fish sludge as a substrate for black soldier fly, and is it environmentally beneficial compared to other utilization options?

The objective of this study is to evaluate the environmental impact from fish sludge utilization, from production to consumption, with an LCA. The LCA results will also be discussed. The environmental impacts will then be used to compare scenarios and assess the potential to reduce environmental impacts.

The fish sludge must be collected at the breeding facility, dewatered, potentially dried, and transported to Moss for future use as BSF substrate. Three scenarios and one base case for utilization will be compared, to determine whether fish sludge as substrate could be justified in an environmental perspective relative to other uses. The other scenarios are biogas and fertilizer production, while the base case is to not utilize the sludge. The goal will be to assess different drying and transportation options in the different scenarios. Then the environmental impact will be calculated for all scenarios, which could be used for future decision making. The policy implications of this thesis provide guidance to the animal feed- and fish industry and the Norwegian policymakers.

This thesis starts with an introduction of Pronofa, followed by a literature review on BSF and fish sludge utilization. Then the methodology, life cycle inventory, and scenario analysis are presented. The next part presents the results before discussing them. In the end, the paper reaches a conclusion.

2 Case - Pronofa ASA

Pronofa is company located in Fredrikstad developing new sustainable protein sources [15]. The company was established in 2021, created from Denofa, which have been producing foodstuff for 110 years. Pronofa is working within the area of insect- and tunicate production, where black soldier flies are reared as a component in animal feed. A new factory with increased BSF production volume is planned in Moss [16]

Black soldier fly, Hermetia illucens, belongs in the Diptera order and are frequently used for biotransformation [17]. The BSF is well suited for animal feed because of the high protein and nutrition content [18]. BSF larvae can be fed by a wide range of organic materials, for example rice straws, food waste or fecal sludge [19]. In addition, BSF has a high feed conversion ratio compared with mealworms and crickets. This means that more of the substrate for BSF larvae will be used to build biomass, which leads to greater dividends for animal feed eaten in the next step of the food chain.[19].

With a growing population, the produced biowaste increases as well. Low and middle-income countries are experiencing challenges managing this waste [20]. A potential solution could be to reuse waste as BSF substrate, to relief stress from the waste management and animal feed production. However, the quantity of substrate is a limiting factor. If the production of black soldier fly should expand, Pronofa will require a larger amount of substrate for the larvae. It would therefore be interesting to examine substrate options that are available in a large quantity the entire year.

One substrate option is fish sludge, as fish sludge could be available during the entire year in a large quantity. However, fish sludge is not allowed to be used as BSF larvae substrate by Mattilsynet and EU [21]. Since the fish sludge would be fed to BSFL, the sludge must meet the requirements for animal feed [12]. Mattilsynets TSE regulations, and EC No 1069/2009, 1774/2002 and 183/2005, will ensure that animal products are safe and does not spread infection [13, 14]. These regulations are problematic in a circular economy perspective, as useful resources for BSF breeding becomes unavailable. Multiple studies have assessed the usage of fish sludge as BSF substrate. These studies mostly conclude that fish sludge, and other sludge types with high protein and volatile solids contents, will make the larvae grow efficient [22–25]. Fish sludge seems like a promising substrate, and the regulations could possibly change in the future. However, more research about potential damage from fish sludge as larvae substrate must be done if the regulations should change [26]. Pronofa would like to assess the sustainability of fish sludge as BSF substrate, in case the regulations were to change.

3 Theory

In this section will background theory about the fish industry, sludge usage, and transportation be enlightened. A literature review of previous and relevant studies will be conducted in addition.

3.1 About fish breeding and fish sludge

The most common fish species for breeding in Norway is Atlantic salmon, rainbow trout and char [27]. These species make up 98.8% of the total fish breeding in Norway, based on monetary value. Salmon is the absolute most bred species, with 1 546 121 tons fish in 2021. Asia produces 90% of the bred fish on a world basis, while Norway produces around 2.5%. Still, Norway is the world's largest producer of salmon. The fish farming sector is expected to grow even more in the future [28]. This means that the production of fish sludge will increase as well.

Fish sludge is a term that covers all waste streams from aquaculture breeding facilities. This could be uneaten excess feed or fish feces [29, 30]. Norway produces over one million tons fish sludge each year, which makes it particularly interesting to find new applications in the market for the waste material [31]. The benefits from efficient fish sludge reuse will be important for Norway when the fish sludge production increases [28, 32, 33].

Atlantic salmon could be bred with six different technologies, where two of them are land-based, and four sea-based [34]. The main types of land-based systems are recirculating aquaculture systems (RAS) or flow-through systems, while the sea-based could be open or closed containment. A RAS system will have water treatment in tanks. The water in a RAS plant will be oxygenated, sent through a mechanical filter, CO2 will be removed, sent through a biofilter and an ozone chamber [35]. The mechanical filter will be filtering out the solid waste, while the biofilter will make the sludge into harmless nitrate. This will usually be done by sludge thickening and flow stabilization [36]. Then the water will be released. A land-based flow through system will still treat the wastewater in tanks, but not reuse the water. In salmon production, the hatchery fish will usually grow in fresh water at land until they become smolt. Then the salmon will be moved to open net pens in the sea [27]. This means that fish sludge from one facility could be collected in both freshwater and sea water stages, but in different quantity and with different methods.

In Norwegian sea-based fish breeding facilities, fish pellets and feces will escape the net pens and reach the ecosystem around. This will also apply to fish medicine and other substances. For sea-based fish breeding facilities, the waste pellets and faces are not obligated to be collect for sludge treatment. These emissions could be hard to measure for the facility, but environmental monitoring is required [33]. As opposed to sea-based breeding, land-based facilities are obligated to have some sort of waste treatment before releasing water back to the sea. These requirements are described in the Norwegian "forurensningsloven" and could be fulfilled with different technology options [37, 38].

Even if the sea-based facilities are not obligated to collect and treat their sludge, it might be beneficial to invest in a collecting system. Innovative technologies for collecting and reusing sludge from sea-based breeding facilities are under developing and could be more common in the future. For example, LiftUp have developed collectors for sludge and waste in sea-based breeding systems [39].

In addition to being a potential resource, fish sludge is today considered as an environmental problem [40]. This problem is caused by uneaten fish food and fish feces that contains phosphorus (P) and nitrogen (N). Phosphorus is a limited nutrition that is responsible for plant and algae growth [41]. As more phosphorus reach the water near the breeding facilities, algae will grow abnormally much. This will reduce the light transmission and oxygen concentration of the water, which could make the water unlivable for other species. The algae could also produce a toxic substance that affect other fish and sea animals [42]. Studies have stated that eutrophication might be more than a local problem, but could potentially affect the ecosystem at a global scale [43, 44].

Collecting fish sludge for further use could therefore be sustainable because of the circularity and bioeconomy, but also as the collecting prevent eutrophication. A study by Aubin and colleagues calculated the environmental impact from not collecting the sludge for future use at a RAS facility in France. This facility produced 6100 kg dry matter from fish sludge in year 2000. The results showed that total amount of P emission during year 2000 was 900 kg P and 5830 kg N, when the total production was 70.45 tons farmed fish. Other factors could also affect the P and N emissions that Aubin calculated. Godlewask's study observed a relation between the fish density in fish pens, and the eutrophication impact around, where the impact increased with fish density [45]. Another study by Puigagut and colleague investigated the phosphorus leakage in fish farms with and without a slag filter and concluded that slag filters could reduce the leakage [40]. In addition, installing a filter is the first step in the process of collecting and drying sludge for further usage. The drying process will be assessed later.

As the concentration of fish sludge and waste is low in the circulating water in pens, the treatment of waste becomes more difficult [46]. If the fish sludge is not utilized, the land-based facilities will usually use particle separation techniques [47]. This will filter out the solid particles in the water, but smaller particles will be more difficult to filter. Therefore, a smaller pore-sized filter will make it easier to reduce the total concentration of waste in water [48]. Even the most efficient separation techniques remove around 75-80% of the solid [49]. The rest could then be released in the wastewater. An efficient RAS facility could recycle about 95% of the water, which reduce the water use significantly [50].

As mentioned before, land-based breeding facilities is obligated to sort out fish sludge before releasing wastewater into the sea [29]. More land-based breeding is assumed to be established, which means that more fish sludge with phosphorus will be filtered [51]. The wastewater treatment could be done with multiple technologies and methods. A study by Takeshita and colleague did an LCA to quantify the impact from fish processing wastewater in Indonesia [52]. Five different wastewater treatment processes were selected to be compared in the study. The results showed that electricity production led to most impact in all impact categories. An up-slow anaerobic sludge blanket had the lowest impact compared to the traditional treating option with activated sludge. However, the increased performance was mostly due to the biogas production that would replace electricity. The main takeaway is that the emissions from energy and electricity production have a larger impact on the results. Therefore, it is important to be aware of the carbon footprint of electricity and calculate LCA results with more than one emission factor for the electricity.

Norway produces electricity by mainly hydro power with low GHG emissions. However, Norway also imports and exports electricity from other countries. This will affect the carbon intensity of consumed electricity in Norway [53, 54]. In LCA calculations will the emissions from electricity vary a lot if the Norwegian power production is used rather than the European electricity mix. Zafirakis paper studies the GHG emissions from electricity trading. The results shows that the carbon factor of different countries electricity production varies [54].

The process of fish sludge drying happens in several steps and could be done with several methods. One method is explained by Brod in her research [51]. At first, fish sludge must be dewatered and treated. This is done by sending the sludge through a drum filter and dewater with a belt filter or sedimentation. Then, the sludge will be dried. This is done by a centrifuge or screw press until the sludge get about 30 % dry matter. To reach 90% dry matter, the sludge must be dried thermally. Bioretur offers technology for alternative fish sludge drying [55]. Bioretur's technology will also use the technologies explained by Brod, but the screw press and drum filter are replaced by other components.

Most companies prefer to dry the fish sludge at the breeding facilities, as the cost for transportation, storing and distribution decreases [56]. On the other hand, the drying is an energy demanding process, which potentially could make it a better option to use the fish sludge without drying in an environmental perspective.

Dried sludge could be collected in bags and sent to future use [51]. Fish sludge is commonly used for energy production, fertilizer, or animal feed today [8]. Various aspects of these areas will be studied below, as this will be the main utilization options in this study.

3.1.1 Fish sludge for fertilizers

Fertilizers are substances that provides the right chemical elements to improve plant's growth and productiveness [57]. These chemical elements could be phosphorus, potassium, or sulfur. Fertilizers are distributed into two main types, chemical or organic fertilizers [1]. The organic fertilizers are often by-products, like slaughterhouse waste or fish sludge. The production of chemical fertilizers could create environmental problems, as the process is very energy intensive. In addition, chemical fertilizers can contribute to a high cadmium content in the soil. This is problematic, as humans will absorb cadmium through the food.

Some studies discussed how sustainable bio-fertilizers are more expensive than chemical fertilizers, which makes chemical fertilizers more common and preferred in an economical perspective [58, 59]. Nevertheless, Spångberg conducted a study where the environmental impact from by-product and chemical fertilizer in Sweden were compared, to prove that by-product fertilizers had greater environmental benefits [1]. Slaughterhouse sludge was used as by-product in this study, while the used chemical fertilizer was called NPK 21-4-7. The results showed that replacing chemical fertilizer with by-product sludge would decrease the GHG emissions and the non-renewable energy consumption. Still, the total energy consumption increased when slaughterhouse sludge was used. Acidification and eutrophication potential also decreased. Other studies have also concluded that the biological fertilizers have less environmental impact and could be more efficient [60–62].

The chemical fertilizer used by Spångberg, NPK fertilizer, contains at least 3% nitrogen (N), 5% phosphorus (P), and 5% potassium (K) [63–65]. Together, the fertilizer should contain 20% nutrients. The three substances have different areas of effect [66]. Nitrogen will make the leaves grow and produce more proteins and chlorophyll. The phosphorus will develop the root and fruits, while the potassium will make the stem and root grow. These fertilizers are well suited for south-west Asia, where the soil is depleted and deficient in phosphorus. Mainland China is therefore the largest consumer of NPK fertilizers on a global scale [65].

Reusing nutrition from other sources could reduce the use of chemical NPK fertilizers. For instant could nutrition from diverse types of sludge be reused. Newer research have been done on the topic of recycling nutrition from sludge [67–69]. Most of these studies conclude that the environmental impact is significantly reduced when reusing nutrient from sludge instead of using virgin nitrogen, but most studies use sewage sludge as the by-product source. As opposed to other studies, Jaeger conducted a study with recycling nutrition from an aquaponics system [2]. This means that nutrition would be reused for plants combined with the breeding facility. The results showed that salad produced with recycled nutrition from sludge had significant lower GWP and EP impact. However, the usage of natural resources increased.

As Jaeger's study showed, is fish sludge a by-product that potentially could be used as an organic fertilizer. A couple of studies have examined the use of sludge as fertilizer, and the results have shown that fish sludge fertilizer could improve vegetable productivity [70–72]. However, a study by Teuber and colleague have highlighted problematic aspects of fish sludge fertilizers. The main benefit from using fish sludge as fertilizers is the phosphorus content [73]. Notably, the phosphorus in fish sludge is not directly available for plants, which makes the effect from phosphorus in fish sludge smaller than in livestock fertilizer [51]. Teuber stated that the fish sludge fertilizer will decrease the amount of potassium in the soil as well [73]. Potassium and other inorganic nutrients should therefore be added to the fish sludge fertilizer.

Another type of fertilizer is called Minorga. This is an organic NPK fertilizer produced from fish sludge or other bio residues in Norway [74]. When producing minorga will nitrogen, phosphorus and potassium be added to the dried sludge or bio residue [75]. The bio residue will also be carefully tested for heavy metals and pathogens, as the final product should not contain this.

Fertilizers have strict regulations for maximum heavy metal content. Fertilizer with content above the regulations cannot be used in agriculture [76]. Studies have therefore assessed whether the concentration of heavy metals in fish sludge fertilizer could exceed the regulations. A study by Bioforsk found that the heavy metal concentration in dried and unprocessed fish sludge was low enough to stay within the class of quality zero [77]. On the other hand, Brod states that the high concentration of Zn and Cd will make fish sludge less preferable for fertilizing [56]. The heavy metal concentrations could therefore be an obstacle for the fish sludge fertilizer usage.

Fish sludge does not count as livestock manure in the fertilizer regulations, and cannot be used untreated like other fertilizers, as described in the Norwegian regulation for organic fertilizers [78, 79]. This means that the produced fish sludge is transported outside Norway. Most fish sludge for fertilization is transported to further use in Vietnam [56, 80]. This also applies for an ongoing project with Bioretur where fish sludge is turned into fertilizer [81]. Bioretur's installations for sludge treatment can only be used at land-based facilities, and the dried sludge is turned into minorga fertilizer by Terramerine in Stavanger. The produced fertilizer in Bioretur's project will then be transported to Vietnam.

The main problem with fish sludge fertilizer is the water and salt content [77]. The salt is less problematic in areas with more precipitation, but elsewhere could the salt be damaging for the plant growth. A study from Yogev and colleagues recovered phosphorous in a near zero discharged RAS for fertilizer use [82]. This study concluded that fish sludge from land-based freshwater facilities had low enough salt concentration to be used as fertilizer. Water is mostly considered as a problem because of the higher transportation costs.

3.1.2 Fish sludge for bioenergy

As mentioned above, the salt content in fish sludge could make it difficult to be used as fertilizer. Fish sludge with high salt content could rather be used for biogas production. A couple of studies have assessed methods for removing more salt from the wastewater and fish sludge [83, 84]. Another solution to the salinity problem is presented by Gebauer in her study. This study assessed how saline fish could be used for energy production instead of fertilizer [85]. The gas production was done by a digester, and gas was collected in aluminum bags. The study concluded that the net energy production from one farming license was 80-165 MWh/year. Gebauer studied an experimental system that would be expanded on an industrial level.

The biogas production happens during anaerobic digestion [86]. This is a biological process where bacteria produce methane gas while breaking down carbohydrates, fat and protein [87]. Biomass is added to the digestion to slow down the breakdown process and prevent the gas production from ending. Fish sludge is well suited in anaerobic digestion because of the high organic content with multiple nutrients. The use of livestock manure and food waste for biogas production is a common research area with multiple studies, while fish sludge is less studied [88].

Studies have assessed the opportunity of energy recovery from fish sludge with different goals and different methodological setup. Some studies have investigated how adding fish sludge to bioenergy production will increase the energy performance indicator, while others are assessing whether a zero-waste scenario is possible at a breeding facility [82, 89]. The new area of use for sludge creates new questions for efficiency and implementation. A study by Choi aimed to answer which mixing ratio between fish sludge and wastewater that resulted in the most efficient biogas production. The study used biowaste from fish as an external source of carbon in the anaerobic digestion process [88]. Choi's fish sludge broth got mixed with wastewater for the anaerobic digestion. A 10L cylindrical reactor was used for the mixture, with 4 different mixtures. In this study, the highest energy production was made with a 50:50 mixtures of byproduct broth and wastewater sludge.

Choi's experiment used byproducts from a seafood processing factory, which should consist of mostly fish body scraps. The nutrient and water content in fish sludge from breeding facilities will naturally differ from the content in Choi's byproduct broth. Studies commonly use sewage sludge or slaughter sludge for bioenergy production [90–92]. For instant, the study by Wang that examined the utilization of slaughter waste in anaerobic digestion systems with an LCA [3]. Note that byproducts and waste from seafood or slaughterhouses potentially could be used for other purposes, like dietary supplements and cosmetics [93]. Fish sludge on the other hand, has not a specific area of use in most breeding facilities today.

Another potential byproduct type was studied by Carvalho and colleagues, namely wastewater from a fish processing plant in Portugal [94]. The study assessed the sludge as a valuable byproduct for anaerobic digestion rather than a waste product. This study showed promising results, where the anaerobic digestion of fish sludge produced 700 $m^3\, CH_4$ per ton volatile solids. Caravalho and colleagues studied another type of fish byproducts than Choi, but still not fish sludge from breeding facilities. This reflects how most studies for anaerobic digestion deals with other industries than fish breeding. Reusing fish sludge, and not fish waste, is still a new concept in the research community on a world basis. However, research from NIBIO specializes in using fish sludge as alternative components.

An experiment with NIBIO and Antech Biogas used a pilot plant to examine the possibility of biogas production in farms [87, 95]. A mixture of animal manure and fish sludge was made at the farm, and four reactors produced biogas from this mixture. The results showed that 20% fish sludge was the best relation between animal manure and fish sludge to produce the most gas. This is lower than the optimal ration that Choi found, because Choi used wastewater instead of animal manure. Such a small-scale bioenergy production would potentially be most economical beneficial at the fish breeding facility, as the transportation cost could be excluded.

The option to produce bioenergy from fish sludge and animal manure have been outcompeted until now, because of low electricity prices Norway. However, as the electricity prices rises, bioenergy from waste could be a preferable energy supply method [87].

3.1.3 Fish sludge as larvae substrate

Few LCAs have been done on fish sludge for larva substrate. However, the insect production market is expected to increase toward 2029 in whole Europe [96]. This means that the available LCAs on this subject realistically will increase, especially in Norway. Today, the Netherlands are leading in the black soldier fly production, with the world's largest BSF factory, owned by Protix [97]. France and Germany are also innovative nations in the insect developing. The largest companies within the insect industry, like Protix, mostly use vegetable food waste as substrate [96, 98]. As Norway has such a large fish industry, the number of LCAs on fish sludge for insect production will probably increase in the future.

Black soldier fly could potentially be an important source of animal protein, as the food demand grows in line with the global human population [22]. The insects could be fed with multiple waste sources. Feeding black soldier fly larvae with waste will make the environmental impact low and could potentially make positive tradeoffs in the waste sector. A couple of LCA studies have examined the use of different waste sources for BSF. These studies have used sewage sludge, vegetables, or pig manure [5–7]. In other words, no studies used fish sludge as substrate. Schmitt conducted a study on fish sludge, but not an LCA.

Schmitt's test diet was rejected water from a drum filter at a salmon smolt facility, which consisted of solid aquaculture waste and water [99]. Two heating options were used in this study, one for 90% dry matter and one for 95% dry matter. After drying, the sludge was sent to Protix, the Dutch company for insect products. The results showed that the larvae growth would be more efficient, and the bioaccumulation would be better, if the larvae were fed by another source in addition to the salmon sludge.

There is a reason for the limited numbers of waste sources have been studied for BSF substrate. Many waste sources are not legal for BSF farming today. The European food safety authority stated that chemical or biological danger cold be possible depending on food safety. Biological dangers could be removed with heat treatment, but inorganic dangers like heavy metal will remain in the heated BSF [100]. In Schmitt's study was the safety of each alternative assessed based on inorganic components [99]. Schmitt concluded that heavy metals would be found in the BSFs, which emphasized how fish sludge should only be a part of the larvae feed.

Lalander's study also concluded that reusing waste as black soldier fly substrate would have a high efficiency, as the bioconversion ratio is high for BSFs [22]. When using BSF in animal feed, it is important to feed the BSF with a source that animals cannot utilize directly, to be considered sustainable. The BSF will add another step to the supply chain, which is another step with energy losses. This means that the environmental impact and benefits from a potential substrate is especially important.

Shcmitt's research does not provide the environmental impact from different substrate options. A study by Modahl and Brekke compared different insect protein productions, and the results showed that the substrate had large impact on the environmental performance of the insect protein [101]. This is also confirmed by Ferronato's study, where larvae breeding has the largest impact [7]. Beyers also compared the impact from insect protein with fish meal and soya meal, and the results showed that most environmental impact from insect production came from a large energy demand [6]. All these studies have primarily used a scope where the insect production is in focus, as the usage of insect protein seems to be most interesting. This results in a situation where more research have been done on BSF as fish feed, than the other way around [102–104].

3.2 Transportation; methods and fuels

Transportation creates environmental impact in form of air pollution, water pollution, noise pollution, or indirect interaction with the environment[105]. The combustion of fossil fuels will release nitrous oxides and particles which leads to local air pollution, but also CO_2 that contributes to global warming. In addition to direct emissions will the construction and maintenance of infrastructure lead to environmental impact. Therefore, it is important to include transportation in LCA's, and conduct LCA's on transportation option to find improvements.

The transport sector contributed with about 9 $GtCO_2$ in 2010. These are only the direct emissions, and more than 70% of the emissions comes from road transportation [106]. Numbers from our world in data shows that 16.2% of the global greenhouse gas emissions comes from transportation in 2016, and that 60% of the road emissions comes from passenger cars [107]. However, emissions from freight transport are still large, and contributes with about 6% to 7% of the total global emissions in 1016. This makes the freight transportation sector an interesting subject for LCAs, as these emissions potentially could be lowered by modern technology and fuels.

Transportation is a common LCA topic, which makes the quantity of available studies large. LCA studies that include infrastructure often conclude that manufacturing phase has low impact compared to the use phase of vehicles [108–111]. In addition will the transportation method influence the environmental impact from transportation. Pizzol conducted a study where freight transport by ships and trains had a lower carbon intensity than air and road travels [112]. This is also confirmed in other studies [113, 114]. All over, the intermodal transportation methods usually have lower emissions.

The transport sector is very depending on fossil fuels and will have a challenging time reducing emissions [115]. Therefore, moving toward zero emissions in the transport sector will be a comprehensive task [116]. The European commission stated that the transportation should be on a firm way toward zero emissions in 2050 [117]. They also implied that electrification would play a central part to achieve this.

The main fuel options in this paper are diesel, electricity, and biofuels. All these fuel option have their downsides. Studies have examined the impact from electrical vehicles, and the results shows significant reduction in use phase emissions compared to conventional fuels [118–120]. However, studies from both Helmers and Middelia with colleagues have found that the impact from battery production is very larger. They still concluded that the use phase had such large emission reductions, that the total impact was lower for the electrical vehicles. Except in impact categories like terrestrial ecotoxicity or mineral resource depletion. The results will also be extremely sensitive to the electricity mix.

In 2050 could biofuels potentially be 25% of the used fuels for transportation [121]. A wide range of studies have concluded that transportation with biofuels have lower emissions than conventional fuels [122–124]. A study by Martin highlighted a problem with the emissions counting for biofuels in Sweden. The study showed that that the GHG emissions within Sweden decreased, but the origin of emission was shifted from Sweden to other countries. The reason for this was that raw materials for biofuel production were imported from other countries. A brother use of biofuels could therefore create problem shifting.

The future trends for freight transportation shows that the required energy for transportation will increase until 2050, and the fuels will consist of mainly oil and gas [125]. In a scenario where the 1.5 degrees target is met, the fuels for transportation will consist of more biogas and electricity, and less oil and gas.

Changing to more sustainable fuels could a method for reducing emissions from transportation. Still, there are a couple of alternative options for reducing emissions from transportation, like innovative technology, policies, or transportation measurement. One technological possibility is lightweighting shipping containers, which could reduce 300 million tons CO_2 if they were used globally [126]. Another paper studied how emissions increases with adverse weather, partly because a safer route would be chosen over a fast route [127]. This reflects how multiple factors, like weight and weather, will affect the emissions from transportation. These factors are difficult to predict in theoretical analysis and are often omitted in LCAs.

3.3 Scope and contribution compared to previous LCA studies on topic

When assessing the environmental impact from fish sludge in an LCA, a number of decisions must be made. A fair functional unit must be decided, a scope must be selected, and the relevant impact categories must be sorted out. A couple of life cycle assessments for fish sludge utilization have been conducted, but the research area is still quite new. Some of these assessments are relevant to this study, as the functional unit, scope, and impact categories could be the same.

There is just one study that could be compared to the scope in this study, and this is Cristiano and colleague's LCA [8]. This study assessed the environmental performance of different fish sludge utilization options from a RAS system [8]. The first option for the sludge was to be dried and used as fertilizer or an energy source. The second scenario would use the sludge for energy production in a cement factory. The third scenario used the sludge for biogas production. The fourth scenario used sludge for animal feed. These scenarios were compared with a business-as-usual scenario, where the sludge went through a standard filter before being transported to another treatment plant as wet sludge.

The results showed that the base case scenario had a larger environmental impact in all impact categories, except water consumption. All scenarios had mostly the same environmental performance, but the fertilizer option had a little higher impact than the others. The global warming potential is twice as high in the base case scenario.

Table 3.1 shows previous research on the subject. This reflects how the research area is not that widespread yet, and that most studies assessed fish sludge for fertilizing. Takeshita's and Aubin's studies have a scope that only included the waste handling at the breeding facility [4, 52]. Spångberg studied the impact from by-product fertilizer compared to chemical fertilizer, with a scope around the fertilizer production and use, while Wang has a scope set around the bioenergy production from sludge [1, 3]. Beyers, Ferronate and Modahl have quite similar scopes, where BSF production with different substrates is compared [6, 7, 101]. However, none of the studied substrates are fish sludge.

Author of study	Description of study
Takeshita et al., 2020	Comparing different waste-water treatment options for sea-base facilities with an LCA
Aubin et al., 2006	LCA on eutrophication potential from fish breeding facilities.
Spångberg, 2011	Comparing environmental impact form by-product and chemical fertilizers in an LCA
Jeager et al., 2019	LCA of an aquaponics system reusing nutrition from fish sludge for salad production.
Wang et al., 2021	An LCA on slaughter waste for anaerobic digestion systems
Seng Liew et al., 2023	Studying the use of BSF that have been fed with sewage sludge for bio energy production in an LCA
Beyers et al., 2023	Using LCA to assess different diets for BSF.
Ferronato et al., 2023	LCA of treatment of organic waste with BSF
Modahl and Brekke, 2022	Comparing different insect proteins and productions for usage in the Norwegian fish feed industry.
Cristiano et al., 2022	LCA of dried fish sludge for fertilizer, bioenergy, or animal feed.

Table 3.1: Overview of previous studies and explanation of what they include [1, 3–8, 52, 101]

This study will combine most of the research form table 3.1 into one scope. This will be done by including waste handling at breeding facilities, and a base case with P and N emissions like in Aubin's study [4]. The study will also include both fertilizer and bioenergy production from fish sludge, like Spångberg and Wang studied [1, 3]. BSF production will not be included in this study, like Seng, Beyers, Ferronato and Modahl did [5–7, 101]. Also, the environmental impact from fish sludge utilization will be calculated in this study, which is a substrate option that have been omitted in previous studies. Cristiano's study will be remarkably similar, but the animal feed production will be replaced by BSF substrate [8]. This study will also include something previous studies have not mentioned, namely the option to transport sludge wet or dry. To conclude, none of the previous LCA studies have such a wide scope, with multiple scenarios for fish sludge utilization, and includes a utilization scenario for BSF.

4 Materials and Method

4.1 Method

This section will present the methods used to answer the research question. The main methods used here will be life cycle assessment and substitution. Also, the goal and scope, necessary inventory, and calculations will be presented here.

4.1.1 Life cycle assessment

Life cycle assessment (LCA) will be used to quantify the environmental impact [128]. This method will calculate the impact from all life stages for products or services in four steps [129]. These steps include goal and scope, life cycle inventory, impact assessment and interpretation. A functional unit must also be decided, to compare the performance of various products [130]. For more information, see earlier work connected to the Furuset district heating grid [131]. This LCA will also include a substitution method.

4.1.2 Life cycle impact assessment

Life cycle impact assessment (LCIA) is an LCA step which turns the gathered life cycle inventory into impacts [132, 133]. The selected impact categories will then be sorted into three main categories; human impact, ecosystem impact, and resource depletion.

After sorting the impact categories into the main groups by classification, the categories will be multiplied with their characterization factor (CF) [134]. The CF will turn the influence into equivalents specific for the endpoint impact group. For instant, species.year for ecosystem impact, or DALY for human impact. Then the resulting impacts will be grouped into total endpoint impact.

4.1.3 Substitution

The definition of substitution is to use one thing instead of another [135]. In LCA, substitution means to use a co-product instead of another main-product to produce a product. The co-product will often be compared with another substitutable product, and the environmental impact from the substituted product will be subtracted from the studied system [136]. This is also called system expansion. For example, a CHP uses fuel to produce both electricity and heat. If the main goal with the process is to produce electricity, the heat will become a co-product. The produced heat from CHP could then substitute heat generation from other sources in the room. The alternative heat source could potentially be a natural gas boiler with emissions. Alternative emissions from the gas boiler could then be subtracted from the main CHP process where heat is a co-product, because the production avoided emissions from other heat generation processes. This CHP example could be described as the equations below. Both heat and electricity will constitute to the total emissions (d) for the CHP [137].

$$d_{CHP} = d_{el} + d_{heat} \tag{4.1}$$

The emissions from heat and electricity will be described as the intensity times produced energy. Here is u_{CHP} the emissions from the CHP and y_{CHP} the efficiency for the CHP, u_{heat} is the heat that will be substituted as emissions from another source, and y_{heat} is the amount of heat per kWh input, while y_{el} is the amount of electricity per kWh input.

$$u_{CHP} * y_{CHP} = u_{el} * y_{el} + u_{heat} * y_{heat} \tag{4.2}$$

$$u_{el} = \frac{u_{CHP} * y_{CHP} - u_{heat*y_{heat}}}{y_{el}} \tag{4.3}$$

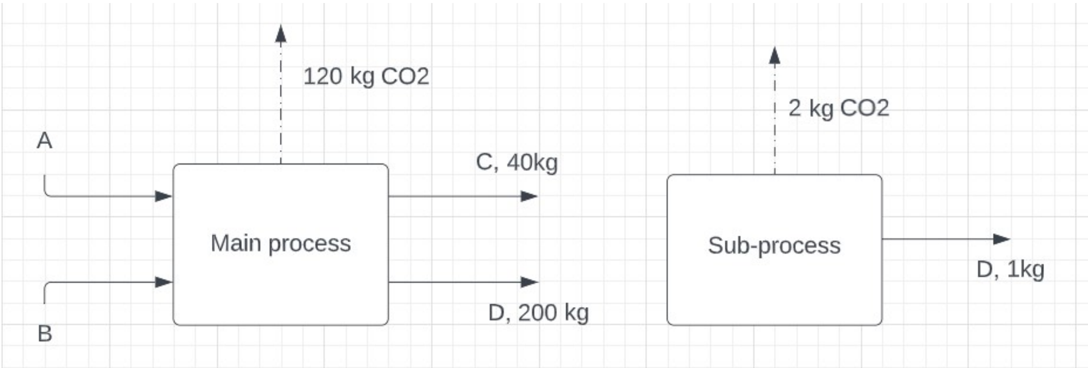


Figure 4.1: Example of substitusition with input A and B, with output D and C. The sub process also has output D.

Figure 4.1 visualizes another example where product D will be produced together with product C in the main process. Since product D is produced from the main process, does not the sub-process need to take place. Then will D from the main process substitute D from the sub-process. If D was produces with the sub-process, 400kg CO_2 would be emitted. Since this is saved emissions, 400 kg will be subtracted from the total emissions in the main process. This results in negative emissions, at -280 kg.

4.1.4 Fore- and background system

The studied system in an LCA is divided into a foreground and background system [138]. The foreground system will consist of processes that is within the decision-making area. These are the main processes in the LCA's system boundaries. The background system will consist of processes that may affect the decision-making within the LCA. This could be background processes that are needed to complete the foreground systems.

One example could be the production chain of an electric car, where the functional unit is connected to the operation of the car. The car will roughly require a battery, wheels, a motor, and a body. This is the foreground system that will be studied in the LCA of the car. However, the battery will require materials and energy to be manufactured. The material extraction and energy production are background processes needed for the foreground system of an electrical car.

4.1.5 Standardized module for life-cycle scope

Figure 4.2 shows how the life cycle inventory will be sorted into five stages with associated sub-stages [139]. This is frequent practice for LCAs in the building industry, but most EPDs use the same setup when distributing impacts as well [140]. Calculating LCA results relative to this standardized scope could make the study more straightforward. The figure below shoes how the A stages is connected to manufacturing phase, B is connected to use phase, C is the end of lifetime, while D is the recycling phase.

A1-A3			A4-A5		B1-B7							C1-C4				D
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw materials	Transportation	Maufacturing	Transportation	Construction installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transportation	Waste handling	Disposal	Reuse and recycle

Figure 4.2: Standardized module for life-cycle scope where the lifetime is divided into different sections [139, 140]

4.2 Research process

This section will present the process behind this LCA step-by-step. This corresponds to the four LCA steps. The goal and scope, life cycle inventory, and impact assessment will be explained in this section.

4.2.1 Logistic overview

The location of the black soldier factory is set to Moss. Land-based fish sludge will be produces in three different hypothetical locations, based on known land-based facilities in Norway. One facility will be in Fredrikstad, Molde and Andøy [141–143].

The sludge will not be dried in Moss, but at the fish breeding facilities. This drying will be done with a number of processes and machinery. After drying, the sludge must be transported from the facility to the use area or further processing. The use location will be in Moss for substrate use, Vietnam for fertilizer, and Ås for biogas production.

4.2.2 Goal and scope

The goal of the study is to answer whether fish sludge for BSF production could be a sustainable utilization option. The LCA method is chosen to account for all environmental impact along the line and saved emissions from substitutions. Environmental impacts will then be observed in all life stages, as well as the upstream impact. Since the utilization of fish sludge will require more infrastructure, it will be important to study the construction of machinery in addition to the energy consumption in use phase. Therefore, an LCA is conducted, to study the total environmental impact from utilization possibilities during the infrastructure's lifetime. The results could later be used in the decision making for BSFL substrate or other fish sludge utilization.

If different usage of fish sludge will be assessed, they need a similar functional unit. Usually, the functional unit is described as a fixed amount of output. This could be difficult when the final product for each utilization is quite different and gives different outputs. However, a functional unit is made independent of the final utilization in this study. The functional unit is: one ton fish sludge for future use in dry mass. The study by Cristiano and colleagues used a similar functional unit [8]. Cristiano's study used a ton farmed fish as the functional unit, to avoid the problem with different outputs. This functional unit should make it possible to compare the different scenarios and options. Also, the functional unit is decided regarding the theory in ISO 14040 and ISO 14044 [129]. The scope of this study will be similar to Cristiano's scope as well.

Scenario name	Description of fish sludge use and processing
1A	For BSF substrate + Dried before transported
1B	For BSF substrate + Transported wet
2A	For Biogas production
3A	For Fertilizing use + Dried before transported
3B	For Fertilizing use + Transported wet
Base Case	Not utilized

Table 4.1: Scenarios and options for the fish sludge utilization. The numbers represent scenarios and the letter represent options.

Figure 4.3 shows the entire system and scope in detail. Circles shows the necessary input to each foreground system. Materials for processes will be produced, transported, and dismantled. The system is therefore a cradle-to-grave LCA, from production to demolition of machinery. The environmental impacts from processes are considered in as well. Figure 4.4 also shows that the fish sludge must be gathered and transported before being utilized, and in some scenarios must the fish sludge be dried. The system boundaries are set around the system and will limit how comprehensive the study is.

The system boundaries are set as shown in figure 4.3. The assorted colors show the different scenarios. Scenario 1, the green box, uses fish sludge as BSF substrate. This scenario is sorted into two options, which could be seen in table 4.1. The first option for scenario 1 dries the fish sludge before transporting it (1A), while the second option transport the fish sludge without drying (1B). The blue and second scenario use fish sludge for biogas production and has no other option than drying before transportation. Biogas production will follow NIBIO and Antech Biogas setup for a small-scaled bioenergy plant [95]. The third and orange option uses fish sludge as fertilizer. Here, the fertilizer could be used in two different options. This first option dries the fish sludge, and the second option uses the fish sludge without drying. The third scenario will use Brod's studies on fertilizers as a starting point, where fish sludge is turned into minorga [56]. The last scenario, called the base case, does not utilize the fish sludge. In this scenario will fish sludge be filtered, and the wastewater will be released into the sea, as in Aubin's study [4].

The geographical boundaries are set over a broader area. The boundaries start from the inlet of the tank or drum filter in Molde, Fredrikstad, or Andøy. Within the geographic boundaries are the drying machinery at site, and potential further processing at the use location. The traveling distance will vary with different scenarios and options. The geographical boundaries ends when the fish sludge arrives at the location and is ready for use.

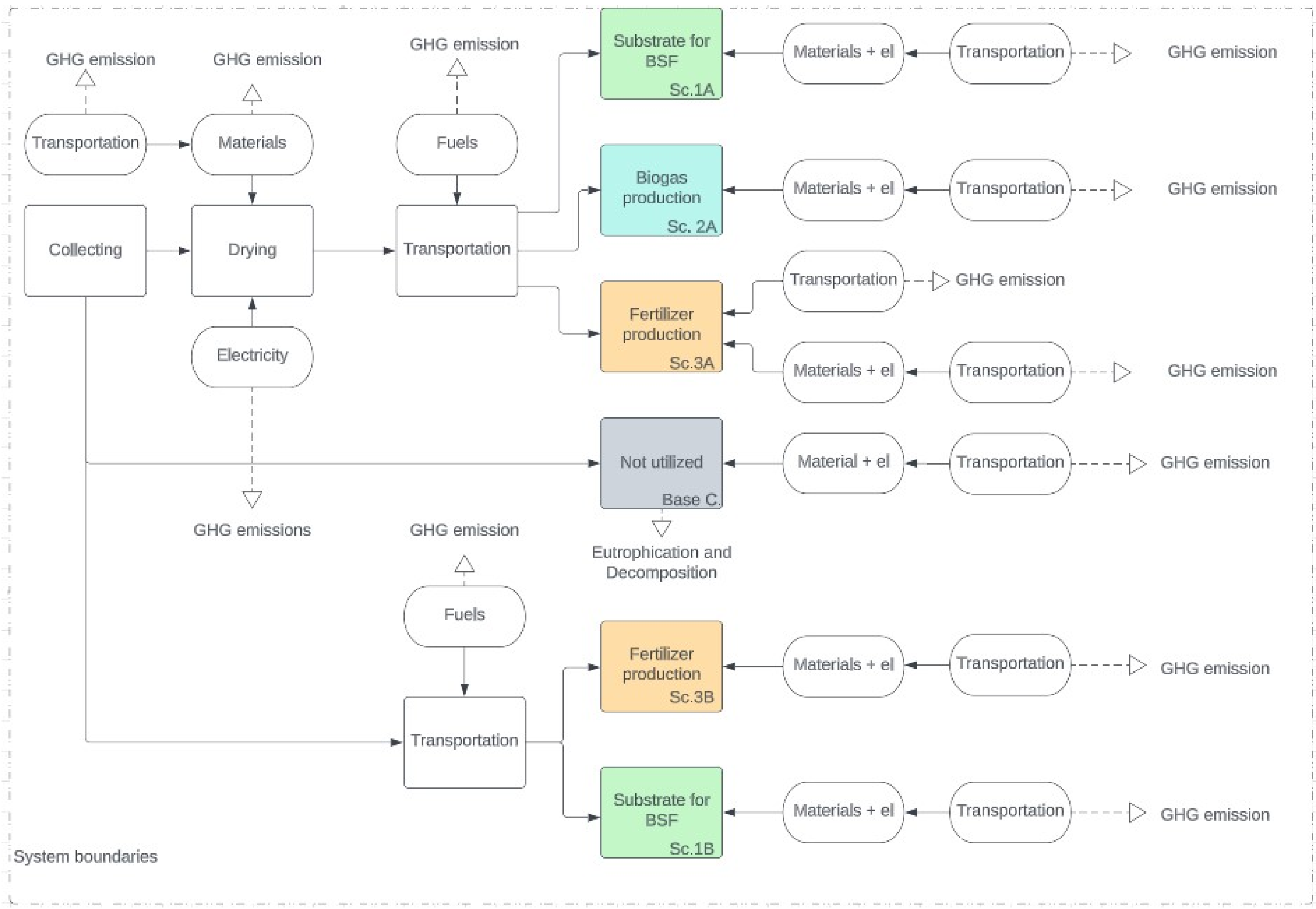


Figure 4.3: Detailed system definition and boundaries. Scenario 1 is shown as green, scenario 2 as blue, scenario 3 as orange, and Base case as grey.

In the end will the midpoint impact be turned into endpoint indicators. This is done by ReCiPe characterization factors from the National Institute for Public Health and the Environment [144]. These factors are shown in table 4.2. The CO_2 emissions will be multiplied with the global warming factor for terrestrial and freshwater impact, the P emissions will be multiplied with the eutrophication factor for freshwater, and N emissions with the marine factor. The new metric will then be species per year. When the three damage areas are added, the result express the total ecosystem damage.

Category	Unit	Hierarchic value
Global warming (Terrestrial)	species.year/kg CO_2-eq	$2.8 * 10^{-9}$
Eutrophication (Marine)	species.year/kg N-eq	$1.7 * 10^{-9}$
Global warming (Freshwater)	species.year/kg CO_2-eq	$7.65 * 10^{-14}$
Eutrophication (Freshwater)	species.year/kg P-eq	$6.71 * 10^{-7}$

Table 4.2: List of the used CFs in this study, with impact category and unit [144]

Endpoint characterization was chosen to make the GWP and EP impact comparable [145]. Cristiano and colleague's study used midpoint indicator, which made it harder to decide which scenario had the smallest impact [8]. Even if most LCA studies on this topic uses midpoint indicators, is species.year a common metric in other LCA subjects [146–149]

4.2.3 Processing at breeding facility

This stage happens either in Molde, Andøy or Fredrikstad. Here, the sludge could be dried before transportation, or collected for transportation without drying. Each component in the drying stage is shown in figure 4.4 and will be further explained in this section.

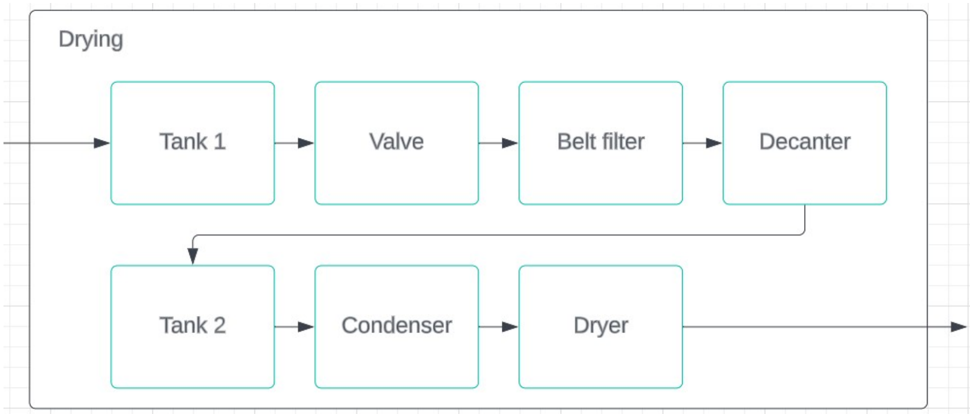


Figure 4.4: Dewatering and drying process divided into smaller parts and components

The main requirements for the dewatering process will be machinery. There are a wide range of dewatering and drying methods used in Norwegian aquaculture [56]. A couple of facilities use a drum filter, belt filter, screw press, and then a belt dryer. The fish sludge could also be filtered, dewatered, and then dried with mechanical fluidization and superheated steam. Potentially, Fjell technology group have replaced the screw press and band dryer with a TMD friction dryer [56, 150]. Fjell technology also supplies most machinery to Bioretur's dewatering system.

Bioretur's supply chain is used as a starting point in scenario 3, which makes it natural to use Bioretur's machinery setup in this study. Note that Bioretur uses a different system than most literature [55]. Bioretur uses a collecting tank, belt filter, decanter, and a superheated steam dryer. This system has more details than the ones in literature and might be more realistic.

Information about the dewatering and drying technologies is taken from data sheets. These data sheets includes the used materials and total weight, but the weight of each material in the product is excluded. Therefore, a roughly estimate is made for each product. Most machinery have stainless steel as their main material. Since stainless steel is a material with high density, a substantial proportion of the machinery weight is assumed to be steel [151].

All scenarios with an A in the name will undergo the same dewatering and drying process. At first, the sludge will be collected in a tank. The input to this tank will have about 0.1% to 0.5% dry matter. The storage tank is made in stainless steel 316L and assumed to have an inner diameter at 0.8m, wall thickness at 0.02m, and a height at 1m. The weight is then calculated with stainless steel density and volume calculations for a cylinder A.1.

The wet sludge leaves the tank in pipes with a valve. The pipes are assumed to be made in stainless steel as well, and have diameter at 10 cm, and a wall thickness at 5.7 mm. This results in a weight at 7.44 kg/m after volume calculations [152, 153]. The cast iron valve is assumed to be a raised face valve with DN 50 at 21 kg [154].

From the pipes will the sludge enter a belt filter. Research from Brod and colleague used a Salsnes belt filter for the fish sludge samples. This study will also use a Salsnes belt filter, namely the SF2000 model [56]. Technical data sheets from Salsnes tells that the belt filter mostly consists of stainless steel 316L, and weight 530kg [155]. The belt material is synthetic reinforced mesh. A small amount of other materials are assumed to be used as well, and the weight from these materials is considered. Average electricity consumption for one belt filter is between 1.8-3.6kW, which makes an average consumption at 2.7 kW.

New pipes with a diameter at 73 mm, wall thickness at 5.7mm, and weight at 5.25 kg/m leaves the belt filter [152, 153, 156]. The sludge then enters a decanter. The decanter is made in Duplex Stainless Steel, cast iron, and AISI 316 Ti steel [157, 158]. HAUS's decanter have a total weight around 65 kN, where the frame weights 38kN, and the motor weights 18 kN. This is an exceptionally large decanter and could potentially be overestimated for Bioretur' use. A similar but smaller decanter at 900 kg is assumed to be used instead [159]. Here is the weight of cast iron and other materials for the motor assumed to be included in the 900kg, while the operational power is 14kW. The sludge will be temporary stored in a new tank before dried. This tank is assumed to have an outer diameter at 0.84m, and a height of 1.8m. The pipe from the tank is assumed to be like the pipes leaving the belt filter.

A condenser is connected to the decanter and tank. This will prevent odors and recover heat. The condenser is assumed to be similar Bitzer's smallest condensers, for example the K123H [160]. This condenser weights 14 kg, and consists of copper, carbon steel, and cast iron. Most weight comes from the carbon steel, which makes up the tube and shell. The copper is used in heat exchange tubes and will contribute with a larger part of the weight as well. This condenser has a capacity at 14.8 kW.

From the tank, the sludge will be pumped into the dryer. Bioretur's dryer uses superheated steam (SHS) for the drying process, with a SHS-dryer. This is the largest part of fish sludge treatment, based on size. However, Bioretur has not specified what type of dryer this is but mentions the use of heat recovery. There are a wide range of SHS dryer, but the assumed SHS dryer will be like Shincci's integrated waste-heat sludge dyer, SHS1000WH [161, 162]. This weight 8.6 tons and consists of mainly steel. Stainless steel is used for pipes and surfaces. The SHS dryer is complicated, with many components. Therefore, a rough assumption has been made that most weight is from stainless steel, some from Polyethylene, cast iron, and other materials. The operational energy requirement is around 34 kW electricity, and 360 kWh heat energy. The electricity could operate a heat pump in the dryer to generate heat. In addition, the SHS dryer could use recovery or waste heat, which reduces the emissions from heat production with a factor at 0.7. The dryer is assumed to use waste heat, recovery heat, and the heat pump 30% of the time, and this heat is not connected to any additional environmental impact. The other 70% will be generated with another source which releases emissions. The pipes leaving the dryer is assumed to be similar the previous pipes.

A couple of pumps will be required to transport the sludge and water through this system. There is assumed that 4 circulating pumps are used for this purpose [163]. These pumps weights 2.7 kg in total, and consists of mostly cast iron, but also ceramic, stainless steel and polyamide. The pumps require 25 kW electricity each.

The environmental impact is calculated by emission factors taken from EPD's. For stainless steel, a EPD of stainless-steel plates from norsk stål is used [164]. These plates are assumed to be processed at the factory in Poland. The carbon steel is also assumed to be used as sheets, while the copper is assumed to be in the form of a wire [165, 166]. Heat energy in this study is compared to an EPD for district heating, where the emissions factor is based on 0.9 kWh delivered heat energy [167]. A bold assumption had to be done for the ceramic parts, as no EPDs were conducted for this. The ceramic in pumps were assumed to be like the ceramic in tiles, where 1 m^2 tiles weight about 20kg [168, 169]. Polyethylene is assumed to have the same environmental impact as polyethylene pipes, and the polyamide as yarn [170, 171]. The emission factor for cast iron was taken from vegLCA's database, because the EPD's for cost iron were considered unrealistic for this study [151, 172]. In addition have emissions from assemble energy been added to the manufacture process. This energy would combine the materials into the machine.

When collecting numbers from EPDs have transportation been deliberately omitted, as the transportation emissions are calculated separately. All machinery must be transported to the breeding facility. Since Fjell technology have cooperation with Bioretur, there is assumed that Fjell is the technology supplier for this study [173]. Fjell technology has their head office in Bergen, but the manufacturing is assumed to be outsourced [174]. The metal processing factory is located in Poland, so the manufacturing is set to this location [175]. The whole machinery is assumed to be transported from Poland to the breeding facility. The distance from Poland to Molde is 1925 km by road, 2 899 km to Andøy, and 1353 km to Fredrikstad [176]. Materials are assumed to be produced locally in Poland, with a distance at 50 km, as vegLCA have recommended [177]. All transportation is assumed to happen by truck, using diesel as fuel, because the materials will be transported in the start of the life cycle where diesel is the most common fuel.

In Cristiano's study, the machinery and structures had a lifetime of 20 years [8]. This study assumes that the dewatering machinery have a lifetime at 20 years as well. The lifetime will be the limited factor for the life cycles length, which gives the whole assessment a lifetime at 20 years. To quantify the environmental impact during the whole lifetime, an assumption about the delivered sludge's weight must be made in addition. According to Cristiano and colleague's study produces an average breeding facility 6.1 tons sludge each year in dry matter. With a lifetime of 20 years, 122 tons sludge in dry mass is assumed to be produced.

The materials in the machinery could either be recycled or not. The machinery is initially assumed to not be recycled, but the results will be calculated with recycling as well. Whether the materials will be recycled or not will depend on the material processing, wear and tear, and the facilities disposal routines. If recycled, the D phase from EPDs will be included. Local transportation from the facility to waste treatment will also be included, which means that C2 from EPDs have been excluded and calculated manually.

The emissions from materials, transportation of materials, and manufacturing are described over. In the LCA framework, this is called module A1-A4. However, there will also appear emissions in the operational phase of the dewatering and drying. This module is called B1-B7. The emissions from this phase are assumed to come from maintenance and operational energy.

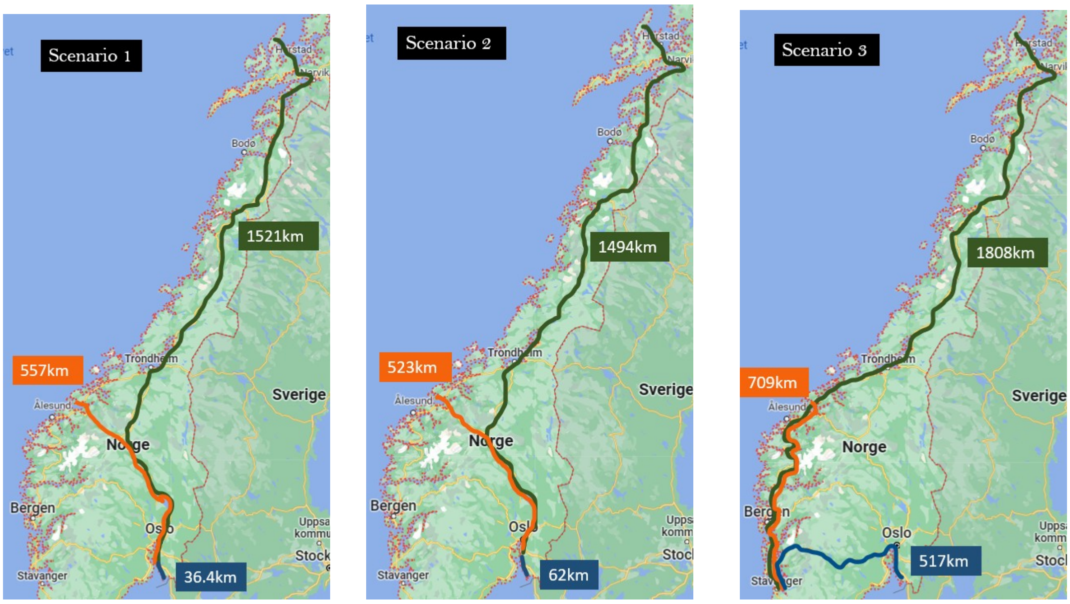
During the 20 years period, 10% of the materials are assumed to be replaced. This is assumed to require 10% of the assembly energy as well. Maintenance materials will be produced somewhere local to the breeding facilities, which results in a transportation distance around 50km. This applies for all maintenance that does not change the whole component.

The dewatering and drying machinery is not assumed to be working every hour of the year but is estimated to work around 4 hours each day. The operational power of each component will therefore be multiplied with the working hours for all 20 years of operation. However, it would seem unrealistic to invest in heavy drying machinery and only use it 4 hours a day for 20 years, because of costs and unnecessary large GHG emissions. Since the GHG emissions from producing the dewatering and drying machinery are large, the GWP per kg dried sludge will be remarkably high. To solve this problem, the emissions from A1-A4 will be multiplied with a "share of lifetime" factor. This factor is calculated by predicting the achievable working hours for the machinery in 20 years. This way, the facility could use the machinery for other purposes, or possibly use it for more than 20 years if only working 4 hours a day.

The machinery is assumed to have the ability to operate 5 hours a day in 20 years, to avoid too ambitious numbers. 4 hours is used for the 6.1 tons sludge each day. The other hour could be used for other purposes, saved for a longer lifetime, or could be used to expand the fish and sludge production. This results in a lifetime factor at 0.8. This means that 0.8 of the A1-A3 emissions for the dewatering machinery will be assigned to the fish sludge at 6.1 tons. Note that the emissions from operation are unaffected by this factor, as the emissions from operation are calculated from working hours.

4.2.4 Transportation

In the next stage will fish sludge be moved from the breeding facility to the next location. Figure 4.6 and 4.5 shows the different transportation methods, distances and final locations. The sludge could potentially be used without drying in scenario 1 and 3. This means that the dewatering process will be skipped, and the sludge will be transported with high water content. If else, the procedure above will be followed.



((a)) Scenario 1 ((b)) Scenario 2 ((c)) Sceanrio 3

Figure 4.5: Itinerary for the different sludge options and scenarios with distances within Norway. The orange line travels from the Molde option, the green from Andøy, and the blue from Fredrikstad [176].

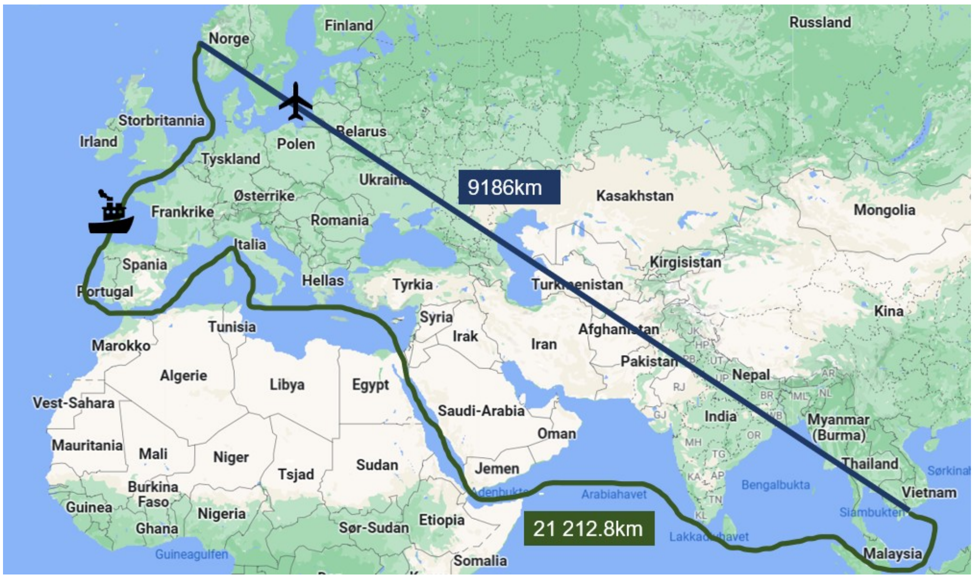


Figure 4.6: Itinerary for transportation by sea or air to Vietnam with associated distances for scenario 3

In scenario 1, the fish sludge must be transported to Moss. From Molde to Moss, the distance is about 557 km by road [178]. The distance from Andøy to Moss by road is 1521 km [179]. At last, the distance from Fredrikstad to moss is only 36.4 km [180]. This transportation is done by truck. In addition, a ferry is needed from Andøy into the mainland, where the distance from Andøy to the mainland is about 24 km in air distance. The transportation with ferry is assumed to have such small emissions that this trip is neglected.

In scenario 2, the fish sludge is transported to Ås. The distance from Molde to Ås is 523 km, there are 1494 km between Andøy and Ås, and 62 km from Fredrikstad to Ås [181–183].

In scenario 3, the fish sludge will be transported to Vietnam. This transportation could be done by cargo ships or plane [184]. The distance from Norway to Vietnam by air is about 9,186 km, while by sea is 11454 nautical miles [185, 186]. 1 nautical mile corresponds to 1.852 km, which makes 11454 nautical miles 21212.808 km [187]. The sludge could be produced in three separate locations, but all location options will send the sludge to Stavanger for future treatment. This transportation is assumed to happen by truck. The distance from Molde to Stavanger by road is 709 km, from Andøy to Stavanger is 1808 km, and from Fredrikstad to Stavanger is 517 km [188–190]. The distance with ship is calculated from Stavanger to Hanoi, while the airplane travel is an estimate from Norway to Vietnam.

Diesel consumption for trucks and ships are taken from vegLCA [151]. A truck for transportation of goods uses about 0.018 l diesel per tkm, while the ship uses 0.011 l/tkm [151]. The fuel consumption from air travel by plane is taken from a study and is assumed to be around 0.187 l/tkm [191]. Emission factors for diesel and biofuels are also taken from vegLCA, and is 2.93 kg CO_2/l for transportation diesel and 1.92 kg CO_2/l for conventional biofuels. The emission factors for electricity are taken from NS 3720, and these values are 0.018 kg CO_2/kWh for Norwegian electricity, and 0.136 kg CO_2/kWh for European electricity mix [192]. Biofuel and electricity demand is assumed to be complementary to the diesel demand. This means that 1 l diesel corresponds to 38 MJ, and 1 MJ corresponds to 0.278 kWh [193, 194]. The vehicle is therefore assumed to use the same amount of energy, independent of fuel type.

Since the sludge will be transported dried or not dried, the emissions cannot be calculated in CO_2 per ton transported. This is because a large amount of unusable water will be transported with wet sludge. The emissions will therefore be calculated depending on the dry mass. Dried sludge has a dry mass around 95%, while sludge directly from the drum filter around 15% [51, 55]. Note that the wet sludge in scenario 3B for fertilization will have a dry mass around 80% after pelleting[195]. Sludge with 80% dry mass will then be transported to Vietnam with plane or ship. Equation 4.4 shows how the environmental impact from transportation was calculated with respect to all information above.

$$I_{transportation} = D_i * F_k * E_k * \frac{1}{S_j} * CF_l * M * 10^{-3} * Y \tag{4.4}$$

Symbol	Explanation
D_i	Distance [km]
F_k	Fuel consumption [l/tkm]
E_k	Emission factor fuel [kg CO2/l]
S_j	Share of dry mass in transported goods [%]
CF_l	Characterization Factor [spesies.year/kg CO2]
M	Dry mass[kg]
Y	Years

Table 4.3: Explanation of symbols used in equation 4.4 [176]

The chosen impact categories for this study are global warming potential and eutrophication potential. However, the eutrophication potential from transportation is assumed to be so small that it is negligible [196]. The impact from transportation is therefore only expressed in GWP. Still, GWP is assumed to affect both terrestrial and freshwater ecosystems.

4.2.5 Further use of fish sludge

After transported, sludge will be further processed before utilized in each specific scenario. This process will be different for each main scenario and will happen at various places in Norway. Each scenario's life stages will be shown in figure 4.7, 4.8, 4.9, and 4.10

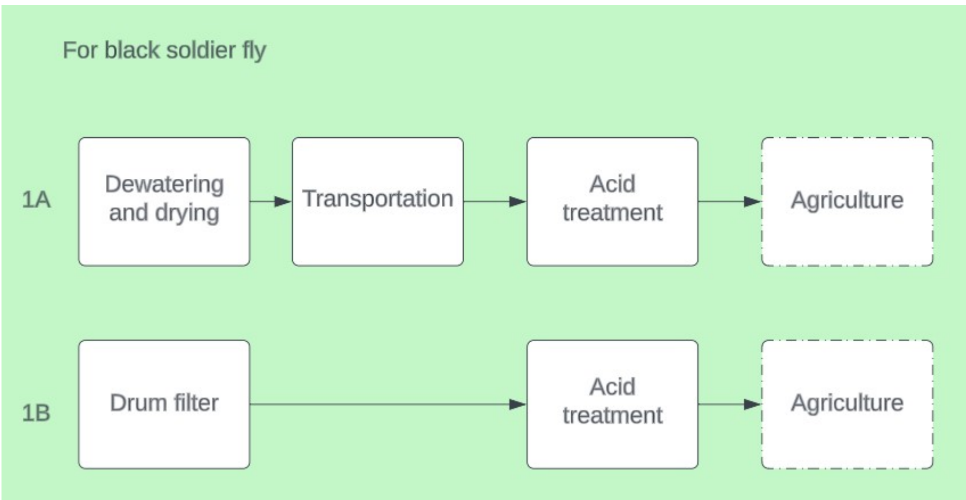


Figure 4.7: Visualisation of scenario 1, where agriculture production are being substituted.

Figure 4.7 shows the A and B options for scenario 1. The substitution will be explained further in section 4.2.7. After being transported, the sludge will go through an acid treatment until becoming silage. The sludge will be fed to the BSF as a part of the diet, where 50% of the substrate will be fish sludge [197]. As shown in figure 4.7, scenario 1B will use a drum filter as in the base case, but without the P and N emissions. The P and N will rather be collected with the sludge for further usage. After leaving the drum filter, the fish sludge will have 0.15% dry weight.

Scenario 1 will send the sludge to Moss for further utilization. Here could the sludge go through multiple possible processed before being fed to the BSFL. Since the BSF breeding is a relative new business area, there is no traditional framework that describes the processing. For reasons of hygiene, the sludge should undergo an acid treatment [16]. An option described in Eltervåg's master thesis will grind the sludge, then go through an acid treatment until the sludge has a pH at 4, and then store the sludge for 24 hours before an additional heat treatment at 85 $^{\circ}C$ for 25 minutes [198]. This process, called silage, will be used in this study as well.

The sludge is assumed to be rather finely ground after dewatering and drying, but three smaller mills will be installed for optional use. It might be more necessary to use the mills in scenario 1B, where the sludge is wet. The mills are mainly built up by stainless steel, weight 6.6 kg, and have an operational power at 450 W [199].

The acid treatment is assumed be done by simply adding acid. An EPD for sulfuric acid is used to quantify the impact from acid production [200]. However, the amount of required acid per kg sludge is much harder to quantify. A study by Gerner and colleagues treated sewage sludge with hydrothermal carbonization [201]. The goal of the treatment was mainly to recover nutrient in the sludge. This study concluded that 349-406 kg sulfuric acid was necessary per ton digested sewage sludge in dry mass. These results gave an exceptionally large quantity of acid, so this study will only use the results as a starting point. Since the purpose of acid treatment in this study is silage, the amount of acid is decreased to 100 kg per tons.

After acid treatment, the sludge will be stored. This is assumed to happen in large plastic containers with a volume at 0.2 m^3. This will result in 3 kg plastic for each container, where the BSF facility will have two in total [202]. Two containers will probably not be enough to contain 6.1 tons sludge, but the idea is that the sludge will arrive to Moss in pools distributed over the year, and the sludge will not be stored for a long time. After storing, the sludge will be heated in a PF800 heating oven at 85 degrees [203]. The oven is assumed to weight 280kg, and the material is mainly steel and cast iron. This oven has a max power at 9000W and a holding power at 3500W. Therefore, an average at 6250W is calculated.

The mills are produced in Staufen in Germany, which is about 1400km away from Moss, while the heating oven is manufactured in Neuhausen 1300 km away [203–205]. The acid and plastic containers are assumed to be produced somewhere local. Maintenance for this machinery is assumed to be negligible. However, the plastic containers are assumed to be changed each 5th year, and the mills each 10th year. The heat cabinet is supposed to have a lifetime at 20 years and will not be replaced during the study. The mills are assumed to be working 5 hours each year, while the operational time for the oven will be calculated based on volume. The volume of the oven is 910L, while 1000L sludge weight 945 kg dry [203, 206]. This means that 6.1 tons sludge will be heated in about 7 rounds in the oven. This is multiplied with three, as most of the oven's volume needs to be unoccupied. The result will then be 21 times 25 minutes in the oven.

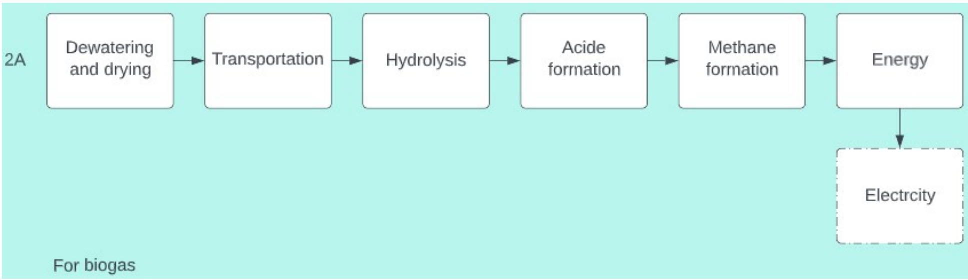


Figure 4.8: Visualisation of scenario 2, where electricity being substituted.

Figure 4.8 shows the one and only option for scenario 2. To produce biogas, the sludge must go through four steps. Hydrolysis, acid formation, and methane formation. This happens in a reactor [95]. There is assumed that reactors at 20L are used for the biogas production. These reactor tanks are isolated with a 4 cm polyurethane layer, while the rest of the reactor consists of stainless steel [95, 207, 208]. A 10L reactor weights 16,5 kg, so it is assumed that a 20L reactor weights twice as much. Plastic or steel pipes will lead into the reactor to refill sludge and feces to the process, while smaller parts are made in rubber. During the process, the mixture will be stirred at 62 rpm electronically, which will lead to an energy demand. The maximum power for the motor is 53W. A detailed data sheet from BPC instruments explains all the used material in the reactor, like stainless steel, PE plastic, polyurethane and rubber. The emission factors for these materials are taken from EPD's [209, 210].

Depending on specific future use, the raw biogas must be cleaned for substances like water vapor and carbon dioxide. However, the biogas is assumed to be used on site in this study, without further cleaning. If the biogas should be used for transportation or fuels, cleaning could be more relevant [211].

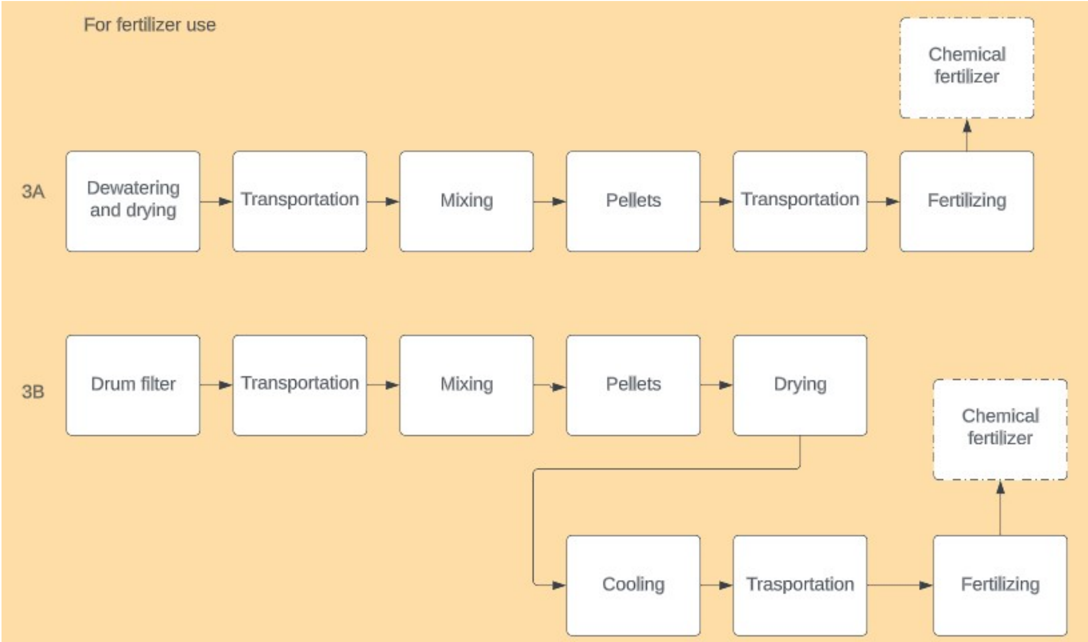


Figure 4.9: Visualisation of scenario 3, where chemical fertilizer is being substituted.

If the fish sludge will be converted into fertilizer, as in scenario 3, the dried material must be processed further. This is shown in figure 4.9. Bioretur's system is used as a starting point in this study. All fish sludge must therefore be transported to Stavanger. Here will the sludge be hygenized and processed further. The fish sludge will then be converted into a fertilizer type called Minorga [80].

Minorga is made by adding nitrogen, Potassium (K), and phosphorus to the dried sludge [74]. The customer can decide the composition of nutrients according to their own needs. To match the alternative urea EPD, it is assumed that the minorga fertilizer will consist of mostly N, with less K and P. The fertilizer is assumed to be converted into pellets with a pellet machine [212]. As the sludge have already been dried and fine grained in scenario 3A, it can be directly placed into the pellet machine. The MZLH350 machinery from Richi is used as a starting point for the granulating. This machine consists of mainly iron and has a protective shield in steel. This pelleting machine has a power at 55kW, and a weight at 3500kg. Richi also provides machinery for mixing, like the "single shaft paddle feed mixer". This is made from stainless steel, has a power around 4kW for the smaller models, and weights approximately 600kg [213].

After the fertilizer granulating, the pellets will usually be dried, cooled and packed [212]. However, this applies to wet sludge, which makes the drying and cooling unnecessary in scenario 3A. The pellets will therefore be packed for transportation immediately after granulating. In scenario 3B, wet sludge is pelleted. This require a drying and cooling process afterward if this pelleting system will be followed in all scenarios. Richi also provides machinery for drying and cooling. A rotary drum dryer is assumed to be used at the plant [195]. The smallest model is about 10 to 12 meters long, cylindrical, with an operating power at 5.5kW. This dryer is assumed to be like a drum filter, just twice as large [214]. Therefore, the dryer materials are assumed to be the same as for the drum filter in the base case, just in a larger quantity.

The fertilizer plant in Stavanger is assumed to use their machinery for other purposes than fish sludge. Therefore, the environmental impact from this machinery should only be allocated to the time where the 6.1 tons of fish sludge are being processed. The mixing machine has a mixing time around 1 minute and can mix around 215 kg sludge [206]. This results in 29 minutes of mixing for one year [213]. The pellet machine has a capacity at 3-4 tons per hour, which leads to a total processing time of 2 hours [212]. The rotary drum dryer is assumed to have a capacity around 1 ton per hours, which results in 6 hours of fish sludge drying [214]. The machinery in Stavanger is assumed to have a lifetime at 20 years as well. The A1-A5 emissions will be multiplied with a factor that describes the fraction of the machinery's lifetime that are used for 6.1 tons fish sludge each year.

The machinery in scenario 3 will also require some maintenance and transportation. Richie is a Chinese company, which is a long distance from Stavanger. Therefore, it is assumed that the same machinery could be produced closer to Norway. Germany is used as a starting point for this manufacturing, and 1200 km is used for the transportation of machinery [205].

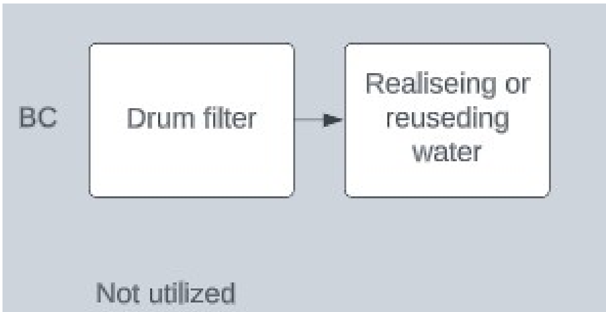


Figure 4.10: Visualisation of the Base case, where the sludge is not utilized.

The last scenario, called base case, will treat the sludge like in Cristiano's base case scenario. This is a simpler system, as shown in figure 4.10. Wastewater treatment will happen in all scenarios, but the other scenarios will collect all the sludge. In the base case, reject water from mechanical filter will be released to the environment, which is mainly water bodies. As the land-based breeding is obligated to collect at least 50% of the sludge, a percentage of sludge will be emitted with the wastewater [215]. The collected sludge is assumed to be sent to a local treatment plant outside the system boundaries.

The fish sludge will go through a drum filter. In this study, the breeding facility is assumed to use a drum filter like the Hydrotech or Smir's drum filter [216, 217]. The drum and tank are made in stainless steel, while the filter panel system, wheels, and main shaft bearing are made in resistant plastics. At last, the filter cloth is made in polyester. If the drum filter is assumed to have a medium size, the total weight is about 730 kg, and the power rating 0.55kW. The emission factor for polycarbonate have been taken from EPDs, while the emission factor for polyester is taken from vegLCA, as no relevant EPD's for polyester could be found [151, 218].

The utilization of fish sludge will prevent phosphors and nitrogen emissions. However, manufacturing of materials will also create EP. These P-eq and N-eq emissions from manufacturing is taken from the used EPDs. Nutrition from sludge will only leak to the environment in the base case, not the other scenarios. This should make the EP larger in the base case than in other scenarios. Eutrophication will be calculated for both freshwater and marine ecosystems, with P-eq and N-eq emissions.

4.2.6 Eutrophication and decomposition

The main sources of P and N emissions are material production and sludge leakages in the base case. The emissions from materials are taken from EPDs. For EPDs with values in $kgPO_4$, the value must be divided by 3 to get kg P-eq [219]. Note that EP impact from EPDs will mostly happen somewhere else than the breeding facilities surroundings.

The base case emissions will be quantified by numbers from Trond W. Rosten's study [220]. The amount of P after filtration was $0.27 \pm\ 0.30mg/l$, and the amount of N was $2,80 \pm 3,42mg/l$. The quantified impact for freshwater eutrophication be around 0.28 mg P-eq per l, and for marine eutrophication will be around 3.11 mg N-eq. [144].

A RAS plant will recycle about 95% of the water, while 5% will be released as wastewater. The drum filter has a maximum capacity at 600 m^3/h, but the filter is not assumed to always be working at maximum capacity. Therefore, the drum filter will have an average capacity at 400 m^3/h. This makes the discharged water 20 m^3/h, or 20 000l per h. With these numbers, the total P and N emissions from 20 years of operation are found.

Another environmental impact is the decomposition of fish sludge in nature. This could be complicated to calculate, so data from previous research will be used here [221]. A study by Sayara and Sánchez states that $2.30 * 10^2$ $kgCO_2$-eq was emitted per Mg dry mass of sewage sludge. This study will assume that the decomposition emissions from fish sludge and sewage sludge will be about the same. The sludge sent to landfill is also assumed to decompose.

4.2.7 Substitution

It is practical to use substitution when assessing the environmental impact from alternative usage of byproducts. With substitution will the byproduct replace another product and reduce the emissions. To make the emission reduction fairer while substituting, two substituting methods are used for all scenarios. The first method will substitute an alternative product, while the second method will substitute the base case.

Substituting the fish sludge in BSF substrate in scenario 1 could be complicated. It would be most realistic to substitute the fish sludge with another waste or by-product, as this is more common within the BSF industry. This would result in a low environmental impact for subtraction, as the impact will be allocated to the main product of the process instead of the alternative byproduct. However, substituting one byproduct with another have less effect on the final results. Another option, which could be considered less optimal, is to produce a main product for the black soldier fly. For instance, grow vegetables for substrate instead of using vegetables waste from restaurants. This option could subtract a larger impact from the fish sludge utilization in sceanrio 1.

An EPD for rabbit feed is used as the substituted product [222]. There is assumed that rabbit feed could be used for black soldier fly, as chicken feed potentially could be used for feed [197]. As mentioned earlier, the total quantity of dry sludge will be 6.1 tons per year. This sludge is assumed to replace the same amount of rabbit feed. Therefore, the impact from 6.1 tons rabbit feed in 20 years will be subtracted from the end results.

The substituted product for the fertilizer in scenario 3 will either be biological or chemically produced. The biological could be produced by by-products like chicken droppings or slaughterhouse waste, which probably would have a lower environmental impact than the chemical fertilizer. The main types of chemical fertilizers are nitrogenous, phosphate, potassic fertilizers [223]. For the substitution, a nitrogenous chemical fertilizer was chosen, because fish sludge from Bioretur is sent to Vietnam to replace chemical fertilizers.

The chemical fertilizer in scenario 3 is assumed to be urea, produced in Asia. An EPD is used to quantify this impact [224]. This EPD is based on a production in Indonesia, which is a long way from Vietnam. This could be considered by extra transportation and emissions from the trip to Vietnam. However, it is assumed that the same fertilizer production could happen in Vietnam. After all, Vietnam is a larger producer of chemical fertilizers [225]. The upstream, core, and downstream impact from the EPD is therefore used based on production in Vietnam. Another assumption is that urea fertilizer will have the same effect as the NPK fertilizer from fish sludge. This means that the organic fertilizer from fish sludge could replacing chemical urea fertilizer of the same quantity. Also, fish sludge is assumed to have about the same mass after adding nutrient and pelleting. This might be a bold assumption but is necessary to simplify the calculations.

If the substitution for biogas in scenario 2 would follow the same pattern as fertilizer and substrate alternatives above, other gas types could be substituted. However, it could be more interesting to expand the system boundaries to electricity production. Then the biogas production could simply be substituted with other electricity productions. The alternative energy production could be hydropower, wind power or coal power. Hydropower and wind power seems like a reasonable choice, as 86.6 % and 11.8 % of the Norwegian electricity production was made at hydro plants and windmill parks in April 2023 [226]. A Norwegian EPD from Skjerka is used for the hydropower production in this study [227].

Note that biogas could be used for heat production and as fuel [228]. If the biogas production was used as fuel, the comparison could happen with gasoline or diesel. Heat could be compared to heat production from district heating. Nevertheless, electricity is used, as the small-scale biogas production in Ås used biogas for electricity [95].

Carvalho's study stated that one ton of solid substrate could produce 700 m^3 CH_4 [94]. This is used to quantify the produced energy produced from 1 ton sludge. 100 m^3 CH_4 corresponds to 1055 kWh energy [229]. The produced energy per year will then be 45048.5 kWh per year. This energy is assumed to replace the same amount of energy produced at a Norwegian hydro power station.

5 Results

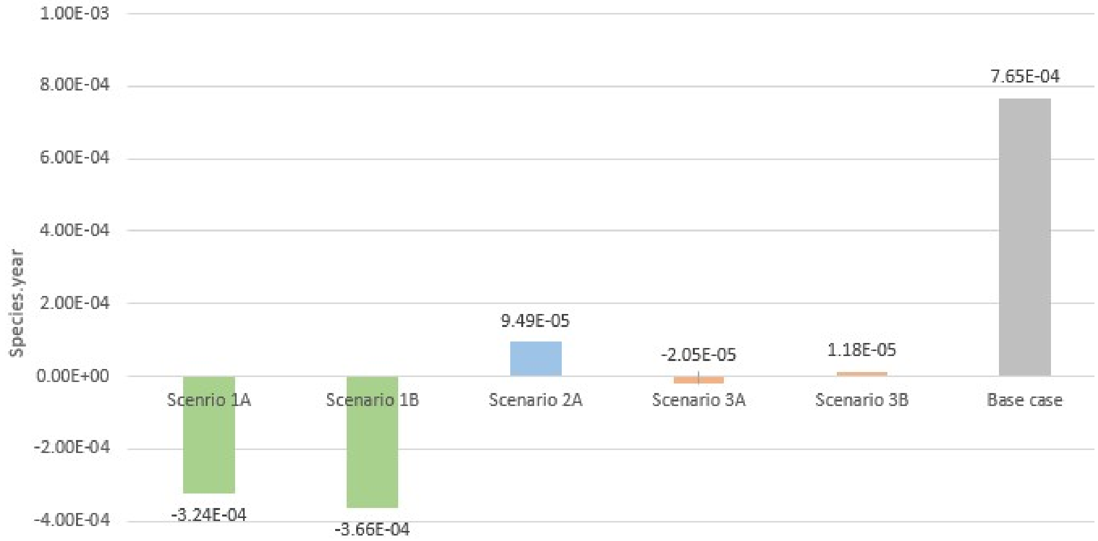
The results of the study will be presented in this section. These results will be sorted into total ecosystem impact, impact from different life stages, dewatering and drying, transportation, substitution, electricity alternatives, and the base case results. The different scenarios are repeated in the table below, 5.1.

Scenario name	Description of fish sludge use and processing
1A	For BSF substrate + Dried before transported
1B	For BSF substrate + Transported wet
2A	For Biogas production
3A	For Fertilizing use + Dried before transported
3B	For Fertilizing use + Transported wet
Base Case	Not utilized

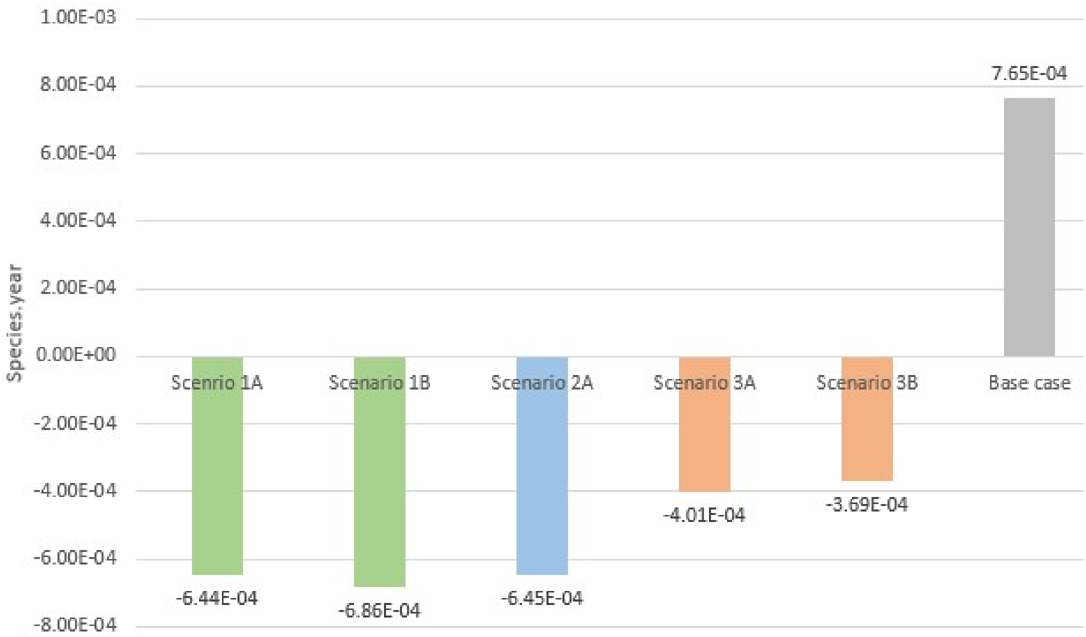
Table 5.1: Scenarios and options for the fish sludge utilization. The numbers represent scenarios and the letter represent options.

5.1 Main results: Total ecosystem impact of different scenarios

Figure 5.1 shows the total ecosystem impact with two substitution methods. Substitution method one will substitute the impact from an alternative product, while method two will substitute the base case impact. The figures below explain how the base case has the largest impact on the ecosystem, and how scenario 1B has the lowest. Scenario 2A will either have the second smallest or second largest ecosystem impact, depending on the substitution method.



((a)) Method 1



((b)) Method 2

Figure 5.1: Total ecosystems impact from all scenarios in species.year with both substitution methods.

5.2 Impacts of different life cycle stages

Figure 5.2 explains in which life cycle stage most ecosystem impact happens. The fish sludge's life cycle is divided into drying/filtering, transportation, and further processing. Scenarios where the fish sludge is transported wet will have largest impact from transportation, while most dried scenarios will have highest impact from drying. Especially scenarios with international transportation will have highest ecosystem impact from transportation. The base case stands out with significantly higher impact from filtering. In addition, all impacts from utilization specific processing are low.

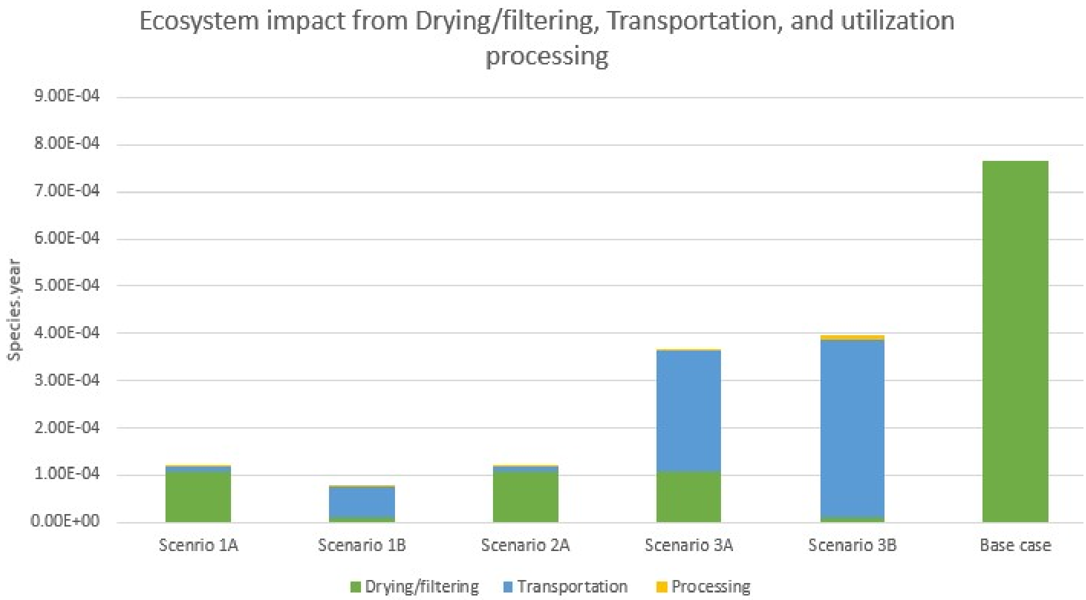


Figure 5.2: Ecosystem impact distributed between the life cycle stages; dwatering and drying/filtering, transportation, and utilization specific processing.

5.3 Drying of the fish sludge

The ecosystem impact from dewatering and drying is described in table 5.2. The terrestrial ecosystem has the largest ecosystem impact for both electricity mixes, while marine ecosystem has the lowest impact. Also, only terrestrial ecosystem impact will be affected by the electricity mix.

Figure A.1 in the appendix shows GWP from specific parts of the dewatering and drying machinery. This figure expresses emissions from production of materials, transportation of materials, assembly, maintenance, operation of machinery, and waste management. From figure A.1, contributes the dryer with most emissions, while the decanter and condenser have the second largest emissions. Figure A.2 and A.3 in the appendix show the EP in freshwater and EP marine, where the dryer and condenser also have the largest emissions.

Electricity	Freshwater	Marine	Terrestrial	Unit
NO el	$1.24 * 10^{-5}$	$6.58 * 10^{-10}$	$9.52 * 10^{-5}$	species.year
EU el	$1.24 * 10^{-5}$	$6.58 * 10^{-10}$	$1.74 * 10^{-4}$	species.year

Table 5.2: Ecosystem impact from dewatering and drying machinery at breeding facility. The impact is distributed between freshwater ecosystems, marine ecosystems, and terrestrial ecosystems.

5.4 Transportation

Figure 5.3 shows the ecosystem impact from fish sludge transportation in each scenario, given dried sludge, diesel as transportation fuel, and Molde as breeding facility location. These results show that scenario 3 has the largest ecosystem impact, especially for the air transportation option, while scenario 2 has the lowest.

Figure A.4 in the appendix can be used to compare how different fish breeding facility location will affect the ecosystem impact. Options with Andøy as the breeding locations have the largest impact, while Fredrikstad has the lowest. Figure A.4 also compares the impact with diesel, biodiesel, and electricity as transportation fuels. The ecosystem impact is largest for options with diesel, and smallest for Norwegian electricity mix options. Comparing figure A.4 with A.5 in the appendix, shows the increase in ecosystem impact as the sludge is transported wet. The option with lowest impact from transportation is scenario 1A, when the breeding facility is located in Fredrikstad, and Norwegian electricity is used as fuel.

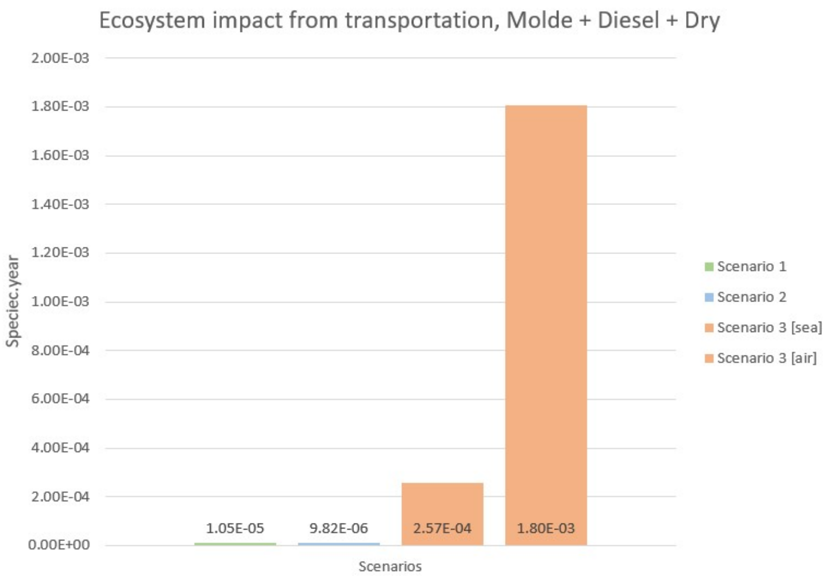


Figure 5.3: Ecosystem impact [species.year] from the three scenarios, when the sludge is dried, and the breeding facility location is set to Molde with diesel as transportation fuel.

5.5 Substitution

Figure 5.4 shows the total ecosystem impact from each scenario compared two substitution methods. The substituted alternative products in method one had significantly lower ecosystem impact then the impact from base case in method two. Also, the impact from utilization is lower than the substituted impact in all scenarios with method two. The substitution has a generally larger impact with method two.

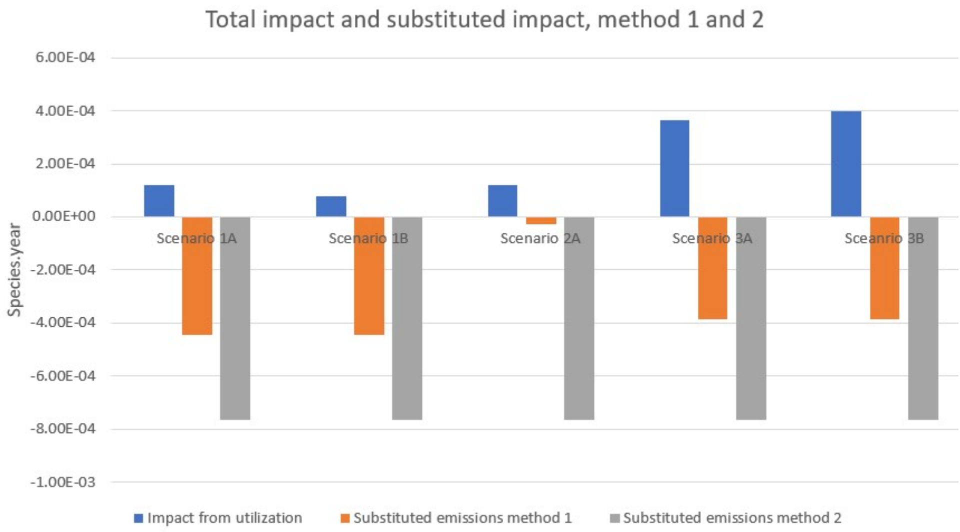


Figure 5.4: Total ecosystem impact compared to substituted impact based on the two different methods.

5.6 Electricity alternatives

Unlike the other results, figure 5.5 shows midpoint results, because the electricity mix only affect the GHG emissions. The GWP increases the most in scenarios with drying, like scenario 1A and 3A, when European electricity mix is used instead of the Norwegian. Scenario 2 have the largest increase when European electricity is used.

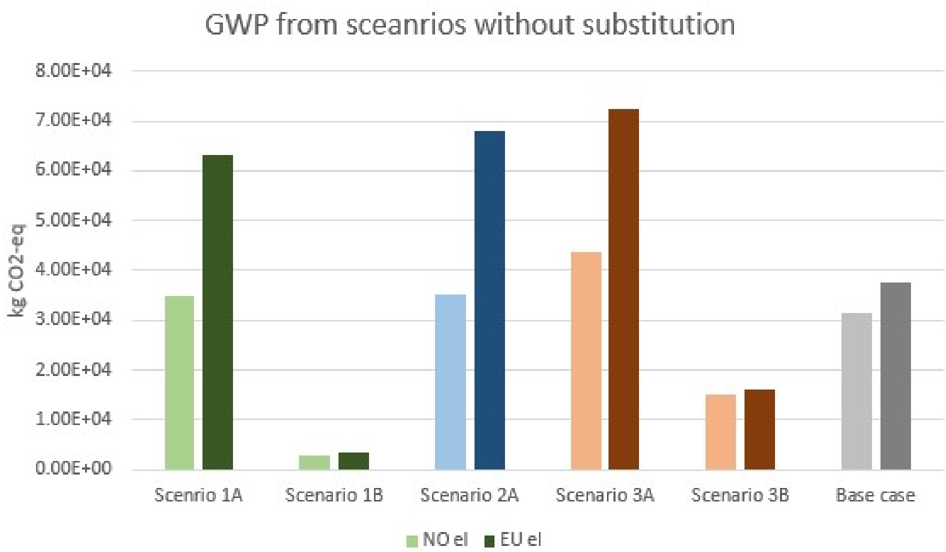


Figure 5.5: GWP in kg CO_2-eq from scenarios without substitution, compared with Norwegian and European electricity mix. Diesel for transportation, Molde as location, and international transportation by sea.

5.7 Base case: Ecosystem impacts of eutrophication and decomposition

The ecosystem impact from P and N emissions in the base case is shown in figure 5.6, together with the impact from degradation. The P emissions have the absolute larges impact for the base case scenario, while the degradation has the second largest.

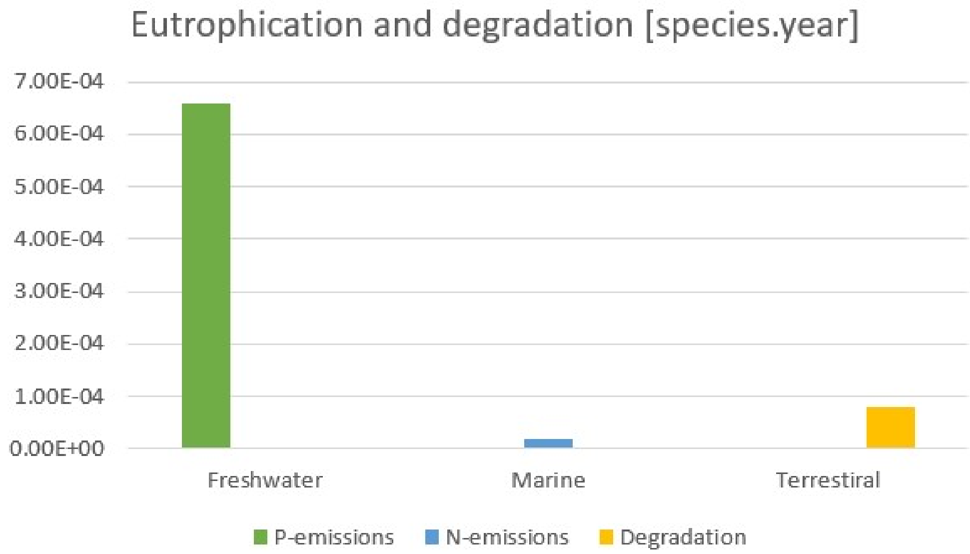


Figure 5.6: Total ecosystem impact in species per year from P and N emissions, and degradation.

6 Discussion

The discussion will be divided into two parts, the interpretation of results and the uncertainties and limitations. The results showed that the scenario where sludge was transported wet for BSF substrate had the lowest ecosystem impact, while the base case without utilization had the largest impact. These results will be discussed in more detail, and uncertainties will be enlightened.

6.1 Interpretation of Results

This section will discuss the study's results. In more detail, it will be discussed whether the results were as expected, and if previous research potentially could underpin them. In addition will the reasons behind results be assessed. The main subjects for discussion will be dewatering and drying, recycling of the materials, already existing machinery, transportation, dry or wet sludge, future transportation fuels, eutrophication potential, biogenic emissions, substitution, comparison of scenarios, and a potential grow in the fish industry.

6.1.1 Dewatering and drying

For scenarios with drying, the dewatering and drying machinery had the largest ecosystem impact compared to other life stages, as seen in figure 5.2. This life stage is the only one with marine impact, but the impact is quite small. Freshwater ecosystem impact also contributes to the total ecosystem impact, as shown in table 5.2. However, the largest impact happens in the terrestrial ecosystem, which is mainly determined by the GHG emissions. These GHG emissions also contributes to the impact on freshwater ecosystems.

Looking closer at figure A.1 in the appendix, the dryer seems to be the largest contributor to the GHG emissions from dewatering and drying machinery. The SHS dyer contributes with over 3/4 of the total emissions. Assessing the SHS dryer closer, steel production is the most emitting process. Stainless steel production leads to large GHG emissions, and the dryer require about 7.7 tons stainless steel. Such an enormous amount of steel will naturally lead to enormous amounts of emissions. The dryer contributes with about 1/3 of the freshwater impact, and over half of the marine emissions, as shown in figure A.2 and A.3 from the appendix. Stainless steel in the dryer contributes with most emissions for EP in freshwater, while polyethylene it the main contributor for marine EP.

Without the lifetime factor for dewatering and drying machinery would the ecosystem impact be even higher. This factor might seem strange, but it was necessary to change whether the machinery operates at maximum capacity or not. Bioretur's machinery has a high efficiency, which results in a possibly large output of dried sludge each day. In this study, the machinery has not been used to the total capacity for drying fish sludge. Potentially could the imaginative fish breeding facility be scaled up and produce more sludge. The impact from drying machinery would be the same as without a lifetime factor, but the impact per kg fish sludge would decrease. The lifetime factor is assumed to be a preferred solution as this opens for using the machine for other purposes. Using the same machinery for other products might be inconvenient in terms of hygiene, which this study has not considered. If else, the machinery is assumed to have a longer lifetime than 20 years if it is barely used each day. This assumption might be less realistic and presupposes that the machinery's lifetime is based on wear per working hour. The machinery could potentially be worn without running, or it could be outdated in 20 years. Therefore, the assumption of a longer lifetime might be unrealistic in practice but seems realistic in a theoretical LCA view. However, the factor ended up being quite high, as the sludge was assumed to be treated more hours of the day than fist expected. This resulted in a lifetime factor that did not have such a significant impact.

The lifetime factor did not affect the ecosystem impact from the operational phase of dewatering and drying. Operating the machinery requires massive quantities of energy, especially the heat energy for drying. This corresponds to Beyer's results, where the substrate production was very energy intensive [6]. However, the required heat production was reduced when waste and recovered heat got introduced. The required heat energy was lowered with 30% when only 70% was assumed to be produced for the drying purpose. This assumption was based on Bioretur's explanation of their SHS dryer. Bioretur did not explain which SHS dryer they used, but they informed that heat recovery was possible for the dryer. In addition, the SHINCCI dryer is called SHS integrated waste-heat dryer, which could make heat with a heat pump or waste heat. In other words, even if the required heat energy for drying is extremely high, the dryer could potentially reduce the use energy demand efficiently and let little go to waste.

It seems realistic to assume that heat recovery and waste heat utilization could happen in in the dryer, but 30% waste or recovered heat might be an ambitious assumption. Finding a realistic share of heat production is difficult, as no information about this is to be found, except that it could vary a lot depending on the situation. The share of recovery and waste heat could therefore be lower than 30%, which would increase the impact from drying, and this could potentially be more correct. On the other hand, this study might present realistic demands for the heat. Since the required heat is so high, the breeding facility would probably reach for as much recovery and waste heat utilization as possible, to reduce the cost from heat production. This could justify a high recovery and waste heat factor.

Also note that the heat is assumed to be delivered by a district heating plant close by. The emissions factor for heat have been taken from an EPD and is quite low. This explains why the results are surprisingly little affected by the share of heat recovery and waste heat. The resulting impact would be higher if more heat energy was produced at the district heating plant, but the results were significant more sensitive to changes is the steel and material emission factors. It could also be discussed whether an emission factor for district heating is well suited for the dryer, as the temperature could be too low. The choice of using an emission factor from district heating could therefore make the emissions from drying even smaller.

As mentioned, the results were especially sensitive to the emission factor for steel. Steel production has an exceptionally large emission factor, because the traditional steel production is very energy intensive. Since most of the machinery consists of a large amount of stainless steel will the environmental impact be high. On the other hand, steel is recyclable and usable, which would make the emission factor decrease. Materials were assumed to not be recycled in this study. However, it would be interesting to examine the emissions with recycling, as the emissions from material production became high. It could potentially change the results if steel production had a lower emission factor. Therefore, the calculations were done with recycling, which made the results changed like suspected.

6.1.2 Recycling of materials

The new results after considering recycling are shown in figure 6.1. The ecosystem impact in all scenarios have decreased, but especially in scenarios with drying. When the emission factor for materials decreases will the emissions from dewatering and drying decrease. The effects from recycling are not large enough to change the end results. Scenario 1B is still the option with least impact, while the base case has the highest. However, the difference in impact between scenario 1A and 1B is so small that they could be perceived as equal. The main change with recycling is that the difference between scenario 1A and 1B becomes smaller, while the base case is not affected.

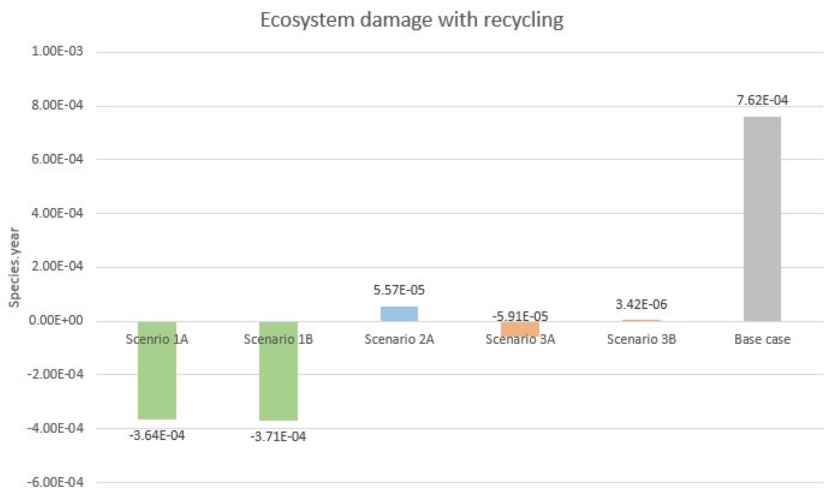


Figure 6.1: Total ecosystems impact from all scenarios in species per year when material are recycled.

It is debatable whether recycling could be likely for all the machinery. It seems likely that some materials in the machinery, like the materials that have been in least contact with the sludge, will be less worn and more recyclable. The dissimilar materials could be well mixed together and difficult to separate, which could make the recycling harder. This was assumed to be the case in this study but could potentially be reconsidered. Some parts in the machinery should be recyclable, and if the technology suppliers create the machinery with circular economy in mind, the machinery could be built with recycling purposes. This means that the varied materials are easy to separate and dismantle [230].

6.1.3 Already existing drying machinery or sharing machinery

This study has assumed that the drying technology must be built and transported to dry the sludge. However, there could be a possibility that the fish breeding facilities already have installed a fish sludge dryer for other purposes. Then it could be discussed whether the manufacturing impact should be included in the LCA of fish sludge utilization.

In an LCA view, a part of the emissions from machinery should be assigned to the 6.1 tons fish sludge, depending on how much of the machinery's lifetime the sludge uses. This was done by the lifetime factor, where every impact except the operation impact were multiplied with a factor. If this concept should be ignored, and the machinery impact were assigned to the breeding facility, the results would change slightly. Figure 6.2 shows how the results changed when the impact from producing dewatering and drying machinery was excluded. The energy demand contributes to approximately all ecosystem impact from drying in the figure below. Transportation and eutrophication also play a bigger role for the endpoint impacts, which makes the drying scenario preferred in an environmental perspective. Scenario 1 is still the best option, but scenario 1A has lower impact than 1B. This shows how the impact from drying machinery have a larger impact than the extra transportation emissions in scenario 1B.

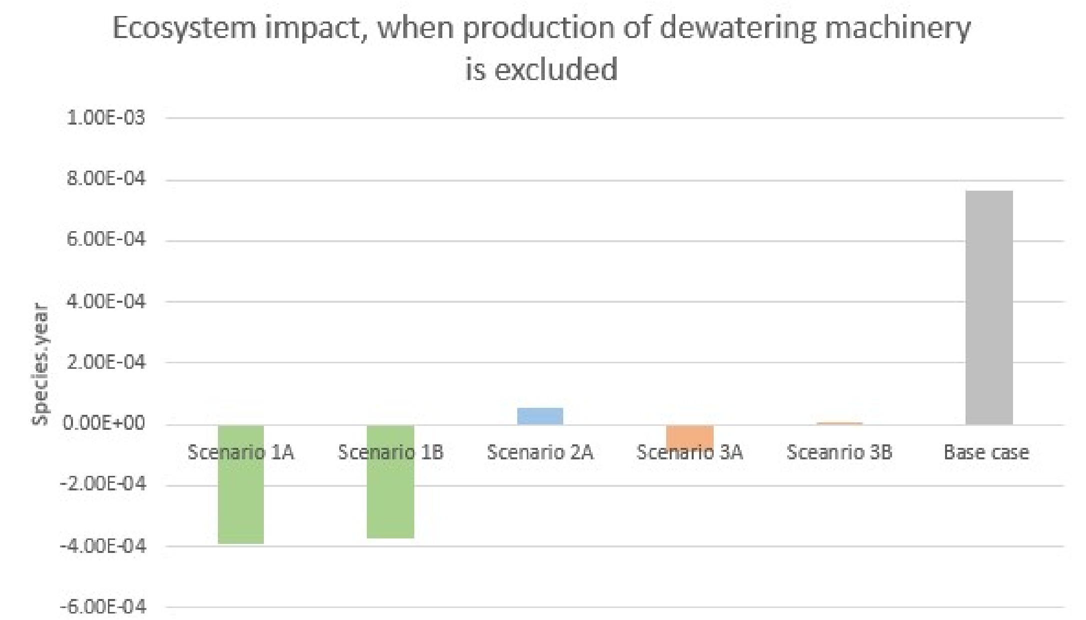


Figure 6.2: Total ecosystems impact from all scenarios in species per year when the impact from producing drying machinery is excluded.

Figure 6.2 is not considered as trustworthy results, as the allocation of impact seems unrealistic. Even if the machinery was already existing, for example is the facility had provided another costumer with sludge until now, should a part of the ecosystem impact be allocated to this study's sludge production. However, the figure could give a clue on how the results would change if simpler drying machinery were chosen. Since Bioretur's large machinery might be overcompensating for 6.1 tons sludge a year, a smaller machinery could be more realistic for one facility. This thought will introduce a new idea.

Since the large drying machinery has a high capacity, it could potentially be shared between different breeding facilities. The three facilities in this study are so far apart that it might be less practical to share machinery, but there is assumed to be more breeding facilities in Norway. If sludge from other facilities was sent to the drying machinery, they could share the impact from production. Wet sludge would have to be transported a short distance before reaching the drying facility. Such agreement could prevent all facilities from investing in the machinery with high environmental impact. However, if this should work, the distance between breeding facility and drying machinery should be short enough to avoid large emissions from transportation. Another solution could be to do the roughest dewatering at the breeding facility, before transportation to a shared drying plant for more thoroughly drying. Then the sludge will be transported with less water, and the heaviest machinery would be shared.

6.1.4 Transportation

The emissions from transportation was as expected in figure 5.3. There was a clear connection between the distance and emissions. The longer traveling distance, the higher emissions. This was also the case for, among other things, Ingrao's and Pizzol's study [109, 112]. The longer travel distance, the more fuels must be used to reach the destination, which leads to a higher environmental impact. This could be seen in figure A.4 and A.5

The connection between emissions and emission factor for fuels was also expected, as shown in figure A.4 and A.5. Diesel has a high emission factor, which contribute to high emissions for diesel vehicle options. Norwegian electricity fuels had the smallest impact, as this fuel had the smallest emission factor. This corresponds to the results from Middela's study as well [231]. Diesel is the traditional fuel, but other alternative fuels could be more common in a near future. To reach the net zero emission goal in the transportation sector should electricity and biodiesel be more frequently used as fuels. The results show how the ecosystem impact could be 15 times lower when replacing diesel with Norwegian electricity. If all vehicles would be replaced with electrical vehicles, the emissions from global transportation would decrease drastically.

Such an emission reduction will also rely on the emission factor of the electricity. The results also shows that the emissions are only 2 times lower if the diesel is replaced with European electricity mix. The manufacturing of electrical vehicles will also have large environmental impact, as Helmer's study showed [232]. With a high enough emission factor for the electricity, and high enough emissions from manufacturing, the electrical vehicle could potential have a larger environmental impact than the conventional diesel vehicle. Still, electrical vehicles seem like the solution to reach net zero emissions in the transportation sector, as direct emissions are in the focus.

Using electricity as fuel might have zero direct emissions, but there could be large indirect emissions from energy production. This also applies for bioenergy, which is considered as biogenic emissions. Still, the process of bioenergy production emits GHGs. The "hidden" emissions have been considered in this study, as indirect emissions are included in the transportation calculations. Zero emissions from transportation will therefore seem unlikely when including indirect emissions. However, a net zero emission scenario could be possible if other sectors compensate for the transportation sector's emissions. As seen in this study, replacing diesel with other fuels could help significantly towards a net zero transportation sector.

Vehicle manufacturing and maintenance is another source of indirect emissions in the transportation sector. The manufacturing of trucks, cargo ships and planes will have large emissions, especially as the vehicles consists of mostly steel and metals. Also, the manufacturing emission would vary with the operational fuel for the vehicle, as other components are required depending on the fuel. Even though the emissions from manufacturing could be large, have these emissions been neglected in this study. The reason for this choice is that emissions from vehicle operation is usually larger, and the vehicles would be used for multiple products. For example, a truck would have a long lifetime where hundreds of tons would be transported each day. If the manufacturing emissions should be distributed to each trip, would the fish sludge transportation get an exceedingly small fraction of the emissions. The emissions from fuel consumption would overshadow the manufacturing emissions in this study.

The final results of this study showed that the emissions from transportation had less impact for scenarios with drying, as the manufacturing of dewatering and drying machinery had larger impact. This gave some rather unexpected results depending on wet or dried sludge for scenario 1.

6.1.5 Dry weight and water content

The fish sludge can be transported as dry or wet mass and both cases were considered in this study. The results showed that the emissions from transportation decreased when the sludge were dried before transported. Transportation of wet sludge had about 6 times larger emissions than the dried sludge. This was as expected, as more water is transported with the wet sludge. The extra water corresponds to unnecessary transportation. However, the interesting results appears when comparing the emissions from transportation of wet sludge with the emissions from constructing the required drying machinery.

If the extra emissions from transporting the sludge wet instead of dry, are lower than the emissions from drying machinery, the transportation of wet sludge could be justified. This was the case for scenario 1 in this study, as shown in 5.1. The total ecosystem damage is higher for scenario 1A than 1B. Such results shows that it would be a better option for the ecosystem to transport the sludge wet instead of dried. On the other hand, scenarios 3B has a larger impact than 3A, because of the higher impact from drying in Stavanger and a longer traveling distance. This reflects how it is complicated to decide whether dry or wet sludge is preferred for transportation.

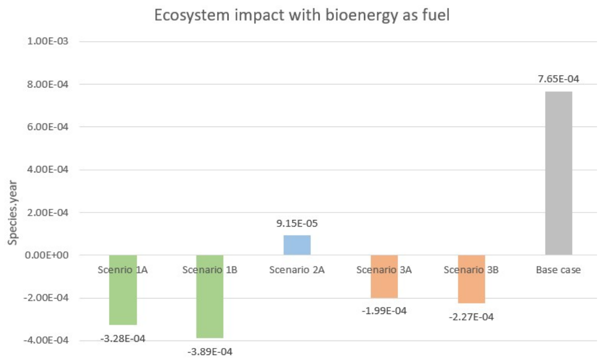
The results from wet or dried sludge could be assessed from different points of views. The main reason to prefer wet sludge is the high emissions from machinery. In this study, the machinery is assumed to mainly be produced for sludge purposes with some additional lending for other purposes. Also, the materials are assumed to not be recycled in the study. This is more discussed in 6.1.1. Another important aspect that makes the impact from drying machinery higher compared to transportation is the level of details. Almost all required materials have been accounted for, in addition to transportation of materials, operational and assembly energy, and maintenance. If the transportation emissions would have the same level of details, the vehicle and road manufacturing should be included in the study, as well as maintenance.

It can therefore be discussed whether transportation and drying machinery should have that same level of details to be compared. The comparison might not be fair as more background system and indirect emissions are included in the calculations for the drying machinery. The emissions from transportation would be higher with more indirect emissions from vehicles and road, but the question is how much larger. It is hard to say whether these emissions would be high enough to make the drying a better option in scenario 1. However, this study has assumed that the excluded emissions from transportation are so low, that the results would most likely be the same.

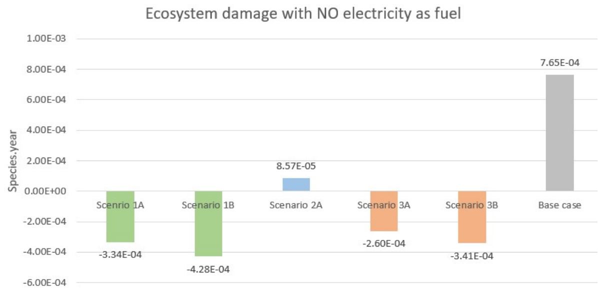
Note that it would be better for the ecosystem to transport the sludge wet, not necessarily economical beneficial for the fish sludge costumers. The breeding facilities will invest in the dewatering and drying machinery, and the investment should be covered by the income from selling dried sludge. If the sludge is sold wet, the costumer must pay the extra expenses of transporting excess water. This could be unacceptable for some companies, which would rather buy sludge from a facility with drying to save money. Especially if sludge should be transported with expensive transportation methods, like air travel. It could be discussed whether air travel for sludge is realistic, as transportation by plane could be more expensive than the transported product. For this reason, sea-based travel is used as the standard in the results. Anyway, the key point is that scenarios with wet sludge might be less realistic depending on the costs.

6.1.6 Future transportation fuels

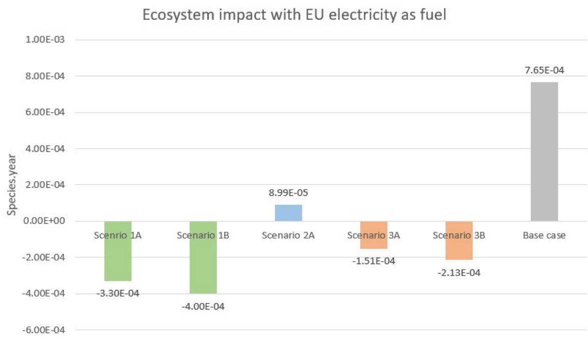
As mentioned earlier could the future fuel consumption change. This could have been captured in this study by changing to biofuels or electricity within 10 years. The emissions from transportation would then decrease. Changing fuels during the 20 years could give more realistic results, but it would also make the calculations more complex. This study has therefore not calculated the results with different scenarios for fuel shifting. Figure 6.3 shows how the final results changes when another transportation fuel is used for 20 years.



((a)) Bioenergy



((b)) NO electricity



((c)) EU electricity

Figure 6.3: Ecosystem impact in species per year with different fuel options for transportation

The ecosystem impact decreased in scenario 1 and 2 when a fuel with lower emission factor was used, but the reduction was not significant. On the other hand, scenario 3 was very sensitive to changes in the emission factor for transportation fuels. This reflects how scenario 3 have larger transportation emissions than scenario 1 and 2. Such results could state that the international transportation should be electrified at first, as this creates the largest impact. At the same time, international travels by sea or air will be harder to electrify, because of the great distance and heavy vehicles. With an effort to decrease the emission factor from international transportation, the impact from scenario 3 will decrease drastically. As shown in figure 6.3, scenario 3A and 3B becomes negative after substitution, and could potentially compete with scenario 1. Reducing emission from transportation could justify the utilization of fish sludge as fertilizer.

6.1.7 Eutrophication and decomposition

Figure 5.6 shows the impact from P, N, and decomposition emissions in the base case. Unlike the other results, freshwater ecosystems have the highest impact, followed by terrestrial impact. Looking closer into the impact calculations, the P-eq emissions have the largest impact. The GHG emissions have significantly lower impact on terrestrial ecosystem, and minimal impact on freshwater ecosystems. The N-eq emissions also have exceedingly small impact.

Decomposition contributes with most GHG emissions for the base case. The decomposition of biological materials will release CH_4 to the atmosphere, which is a stronger GHG than CO_2. The GHG emissions from decomposition will therefore have a substantial impact, as 1 kg CH_4 corresponds to 25 kg CO_2. Even when the GWP is large is the freshwater impact from GHGs minimal. The reason for this is that the characterization factor for freshwater impact per kg CO_2-eq is extremely low. On the other side, the impact per kg P-eq on freshwater ecosystems is remarkably high, which explains why the P-eq emissions have such a significant impact on the environment.

This study has assessed land-based breeding facilities where the sludge is collected, which means the P and N leakage corresponds to a smaller share of the total nutrient content. When the results show that the P emissions have significant ecosystem impact from the land-based facilities, it makes the sea-based more questionable. The P and N emissions would naturally be even higher for sea-based facilities, where the sludge usually is not collected. The enormous CF for P emissions will make these emissions especially crucial. This means that freshwater breeding in pens will have an extremely high ecosystem impact from eutrophication potential. The result from this study shows how important sludge collection will be for future sea-based breeding, as the P and N emissions potentially could reach the ecosystems boundary.

6.1.8 Biogenic emission

The decomposition of fish sludge is biogenic emissions, as the fish feed would contain plant materials [233]. This is emissions that are released by eighter combustion or decomposition of organic materials. These emissions are usually not accounted for in LCA's, as the emissions are assumed to have been absorbed from the atmosphere during the organic materials lifetime [234]. This study has accounted for biogenic carbon emissions by calculating emissions from fish sludge decomposition.

The biogenic emissions from decomposition were included in this study as this would make the comparison between base case and scenarios fairer. It was assumed that emissions from decomposition were avoided when utilizing the fish sludge. To assess the benefits from utilizing fish sludge, the decomposition emissions had to be included, as these emissions would be avoided. The utilization could therefore be used to make the total impact from fish sludge systems negative. This works the same way as carbon capture and storage technologies for bioenergy. Capturing biogenic emissions from bioenergy will make the emissions negative, as the technology can be considered to capture CO_2 indirectly from the atmosphere. The substitution in this study shows exactly this effect for fish sludge utilization.

Of course, if fish sludge happens to decompose during the utilization would the benefit from utilization be overestimated in this study. To avoid such problems, the decomposition could be excluded. If all biogenic emissions were excluded, the results would change. The base case could have a lower impact, while a smaller impact would be substituted in the other scenarios with method two. The ecosystem impact from scenario 2 could actually be higher than the base case with substitution method two. According to LCA framework, this could be a theoretically more correct solution [235–238].

6.1.9 Substitution

Substitution was used to calculate the ecosystem impact from byproduct utilization with two methods. Method one subtracted less emissions than method two. This was not as expected, as method one was supposed to compensate for the larger impact from utilization. The thought was that the sludge would replace other products with more impact, but the sludge happened to have more impact in some scenarios. This is shown in figure 5.4. A simple explanation for this surprising result could be the level of detail. The substitution is only done by an EPD. This EPD should include a large background system, but this is not guaranteed. In addition, more machinery or other materials could be required to use the substituted product. Transportation is not included for the substitution in method one, which makes the impact smaller.

Scenario 1 used rabbit feed for substitution in method one, which had both large freshwater and terrestrial ecosystem impact. The ecosystem impact in scenario 1 became negative after substitution, as the impacts from further processing and transportation were low in scenario 1. This applies to both scenario 1A and scenario 1B. This shows that the substituted ecosystem impact will compensate for the filtering/drying emissions, transportation, and further processing impact. In addition to the compensating, the substitution will subtract even more impact from scenario 1B. The same applies for scenario 1A, but not to the same extent. In other words, the substitution had larger impact on scenario 1B than 1A because the original impact was higher in 1A.

Scenario 2 had the absolutely lowest substitution impact in method one. This is no surprise as Norwegian hydro power is assumed to be replaced. The hydro power had minimal impact per kWh, which lead to almost negligible impact compared to biogas production from fish sludge. This could raise question whether hydro power was a good substitution for the biogas production. If coal power was used instead would the substitution impact be much higher, and scenario 2 would become an option with better environmental performance. However, hydro power is a more likely electricity production in Norway, which makes the substitution realistic. If more imported electricity would be used instead of Norwegian hydro power, the subtracted impact would probably be higher. A middle ground between hydro and coal could potentially be a fairer substitution for scenario 2.

The third and last scenario would substitute chemical urea fertilizer in Vietnam. The substituted emissions are smaller than the rabbit feed in scenario 1. In this scenario will the ecosystem impact from 3A become negative, while 3B stays positive after substitution. This shows how scenario 3A has larger impact than 3B, as the same amount of impact have been subtracted from both.

The second substitution method subtracted the base case impact in all scenarios, as shown in in figure 5.1(b). As method two substituted a larger impact would all scenarios be more effected by the substitution. All scenarios got a lower ecosystem impact with this method, but all scenarios have been reduced with the same amount. In fact, all scenarios became negative, as the base case had the largest ecosystem impact. Subtracting the same amount of impact from all scenarios gave the ulterior motive for using method one instead. Substitution method one would substitute impact based on the utilization. For instant, scenario 3 could potentially get a good environmental performance even if the sludge would go through processing and transportation with large impacts, if it replaced a product with higher emissions. Unfortunately, the emissions from sludge processing and transportation where too high to be justified in scenario 3B and 2A with substitution method one. There could be an option to combine the two methods, as impacts from both base case and alternative product will be avoided with fish sludge utilization.

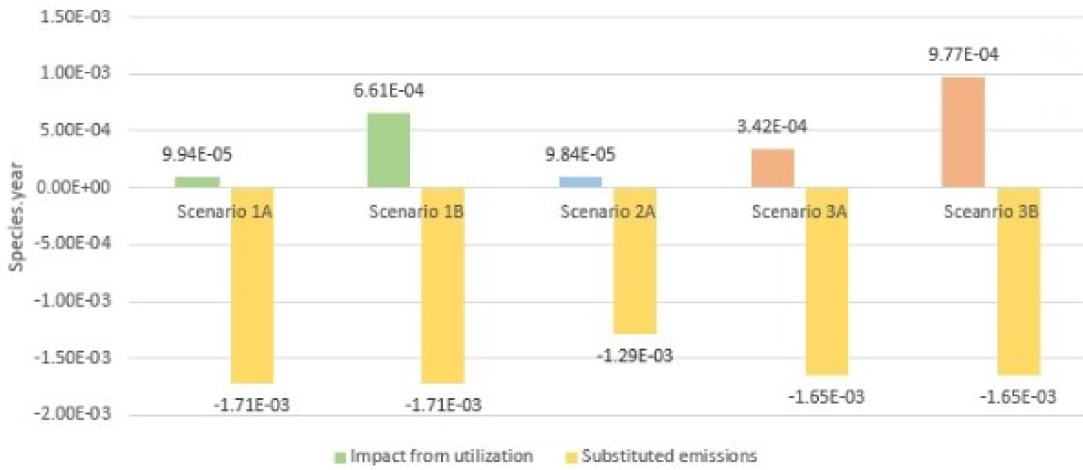


Figure 6.4: Total ecosystem impact from fish sludge utilization compared with the combined substitution method 1+2.

Figure 6.4 shows the total substituted emissions when method 1 and 2 are combined. The ecosystem impact in each scenario have been reduced as much as possible, and all became negative. These results could potentially be even more correct, as both sources of ecosystem impact are avoided with the utilization. This study used two substitution method to compare which avoided emissions where the most important. However, combining the two methods could subsequently seem more realistic.

Theoretically should the impact from sludge utilization become negative if the substitution is good. This did not happen for all scenarios, but this does not necessary say that the sludge utilization is a bad choice for the environment. As mentioned, could the substitution have too minimal impact, which makes the benefit from replacement smaller. It is important to reuse the earth's resources and by-products to achieve a circular economy. Since P is a limited resource, especially in the Vietnamese soil, is reuse and distribution of P resources important. In addition are only GWP and EP accounted for in this study. Reusing resources in a circular economy could give benefits in other impact categories. Also, using by-products could give benefits that cannot be captured by an LCA. Like preventing problem shifting, creating jobs, or increasing the quality of life. The bottom line is that assessing by-products by impact and numbers might not tell the whole picture of benefits in a circular economy.

6.1.10 Comparing scenarios against each other and the BSF scenario

For each scenario's individual utilization, the scenarios needed materials and energy. All scenarios have rather minimal impact on freshwater and marine ecosystems from the utilization specific requirements. The terrestrial impact was a bit higher for all scenarios, except scenario 3A. Since the sludge used such a small part of the heavy machinery's lifetime in scenario 3, became the ecosystem impact from operation and production very small in this scenario. Scenario 3B had more machinery, which lead to more impact than scenario 3A. However, most scenarios had minor impact from the utilization specific requirements, except the base case. This scenario had much higher impact in total than the other scenarios.

The base case really stands out from the other scenarios when assessing freshwater and marine ecosystem impact. The base case has an exceptionally large impact on freshwater ecosystem, as shown in figure A.6(a). This is mostly caused by the P and GHG emissions, as explained in 6.1.7. The other scenarios have either negative or minimal impact on freshwater ecosystem after substitution. The same applies for marine ecosystems, where figure A.6(b) shows how the base case have significant larger impact than the other scenarios. This makes the other scenarios preferable based on these two ecosystems. However, the interpretation could change when assessing the terrestrial ecosystem results.

Base case has higher impact on terrestrial ecosystems than all scenarios before substitution, except scenario 1B. At the same time are the impacts on terrestrial ecosystems higher than the impacts on marine ecosystems. After substituting emissions, only scenario 2 has larger terrestrial impact than the base case. Still, the final results shows that the base has largest ecosystem impact. This shows how the impact from P emissions is significant, and the substitution has large effects on the scenarios. For the other scenarios is terrestrial impact the deciding impact, as marine and freshwater impact are minimal. Scenario 3 had the largest ecosystem impact before substitution, except the base case. Cristianos's study also concluded that the fertilizer utilization had the largest impact in his scenario analysis [8]. This correlation may be coincidental, but the heavy machinery and long traveling distance for the fertilizer could make the utilization less environmental beneficial inn most studies.

The result in figure 5.1 shows that using fish sludge for BSF substrate is the best solution with both substitution methods. If recycling is not considered, scenario 1A and 1B will be the best option. If recycling is considered are both scenario 1A and 1B still the options with least environmental impact. However, scenario 1A has almost the same ecosystem impact as 1B when recycling is considered. Whether recycling is reasonable or not must be decided by before making any decision regarding these scenarios. This explains how the ranking of scenario 1A is very dependent of the recycling, and that wet transportation of fish sludge could potentially be less justified if materials are recycled.

The scenarios should be compared based on the same starting point. In other words, it could be unfair to compare scenario 1A and 3B when deciding which usage has less impact, as the scenarios have different dry mass. If only A or B scenarios will be compared is still scenario 1 the best option. No other scenario has as low ecosystem impact as scenario 1 when only comparing A scenarios. It could therefore be unambiguously that scenario 1 is the best option, while the interesting question is whether the sludge should be transported wet or dry.

6.1.11 Growing industries and the quantity of fish sludge

The fish industry, and the insect breeding industry is assumed to increase. In this study have the supply of fish sludge been assumed constant. This means that Pronofa, or other companies, will have the same stream of fish sludge for the whole LCA period.

This assumption seems bold, as Pronofa production probably will expand, and the available fish sludge will increase with the fish industry. With such an expansion should the stream of sludge to Pronofa increase with a factor for each year. Even with a factor could the expected increased be unrealistic, as the increase could be nonlinear.

However, if the insect industry in Norway increases in the studies lifespan, other companies might compete with Pronofa. This situation could justify that Pronofa's supply is constant. As the fish industry increases, and more sludge is available, other insect companies could utilize the new surplus of sludge. Pronofa will then get the same amount of fish sludge, while new companies will benefit from the expansion of fish breeding. This might not result in a completely fair and realistic distribution between Pronofa and other companies but could be used as an example to explain the concept in further distribution.

Different utilization scenarios have been studied as well, where all fish sludge have been sent to one further use. The study has assumed that only one utilization option could be covered at ones, and that one option must be chosen over the others. This might not be realistic. The scenarios do not have an unlimited need for fish sludge, so sludge could potentially be distributed between all utilization scenarios. The yearly consumption for fish sludge in Vietnam, for Pronofa, and bioenergy production will probably not be covered by one breeding facility. However, the three breeding facilities in Molde, Andøy and Fredrikstad could maybe supply all the usage together. This will obviously presuppose that all three facilities have the same drying machinery. On the other hand, the main goal of the study was to compare different fish sludge utilization options, not to decide which should be prioritized. This means that the study never implies that other utilization will be de-prioritized because of a higher environmental impact than others.

6.2 Uncertainties and limitations

The study has a number of uncertainties and limitations which potentially could make the results more questionable. These limitations are connected to assumptions, the use of EPD's, substitution, impact categories, characterization factors, and data availability and reliability.

6.2.1 Assumptions

Multiple assumptions have been made along the way in this study, and the justification for each assumption should be clear. These assumptions are made to replace missing information or to simplify the calculations. The more assumption, the more uncertain could the study's results become. The ideal situation would be to avoid making assumptions, as all parameters and information connected to the study are known, and the calculations was already simple enough. This is unfortunately extremely hard to achieve in most studies.

Examples of assumptions are operating hours for machinery, weights of machinery, and lifetimes in this study. These assumptions could make the results more uncertain, but they do not necessarily make the results more wrong. If fair assumptions have been made, the results could still be trustworthy. The mentioned assumptions above have the largest impact on the results, while other assumptions could potentially have minimal impact on the results. Assumptions with minimal impact on the results are easier to justify. The mentioned assumptions could also be considered as methodological setup choices, as the breeding facilities are theoretical plants with theoretical machinery and production. The question concerning these choices is therefore whether they seem realistic in practice.

To avoid and detect the impact from assumptions, the results were calculated with multiple parameters. For example, the breeding facility locations, transportation fuels and the emissions factor for electricity were changed during this study. The three locations for land-based breeding facilities should be realistic, as they are based on real facilities. Also, the locations are scattered around Norway. Multiple locations with different distances are preferable, since the facility for fish sludge supply has not been determined. It could be delivered from a location far away, like Andøy, or close by, like Fredrikstad. The future emission factor for electricity and transportation fuels could also be hard to predict. To play it safe, the results were calculated with multiple options for these parameters. As the parameters where changed, the results in each scenario did not change that much compared to each other. Minimal change in the results shows that the assumptions potentially could be justified. However, scenario 3 was overly sensitive to changes in fuel emissions, while A-scenarios were sensitive to changes in electricity consumption. This could Pronofa take in mind if there is an opportunity to choose between multiple locations or electricity mixes.

6.2.2 EPDs

Most emission factors for materials are taken from EPDs. EPDs are often a reliable source, as professionals have been hired to make them. The environmental impact from EPDs is often on a detailed level and good structure. In addition are the EPDs easy to use, as all impacts already have been calculated and are ready for use. However, these EPDs could also create uncertainties in the study because of multiple reasons.

Firstly, the EPDs are produced for specific products. For example, the stainless steel EPD is based on steel sheets. When stainless steel is used for machinery in this study, it is not necessary used in form of sheets. This means that the sheets must be adapted to the specific use by shaping it. This have been considered with extra energy consumption for assembly in machinery. Other assumptions might be bolder. For instant, using an EPD for ceramic tiles for the pumps. This study has assumed that 1 kg ceramic tiles will have about the same environmental impact as 1 kg cast ceramic in the pumps. Still, the EPD has included the impact from cutting and molding ceramic into tiles. This study's inventory choice could be justified if the impact from cutting and shaping tiles will be approximately the same as shaping the ceramic for pumps. In other words, the assumption might be bold, but not necessary completely wrong.

The second problem with EPDs is connected to the product types as well. To get an EPD, the company must pay an external office to conduct the LCA calculations. Afterward, the EPD must be verified by the EPD international. This is a comprehensive procedure, which will require the company the to incur an additional cost. This might seem unnecessary for some companies, and the threshold to get an EPD becomes higher. On the other hand, if a company has an EPD of their product with promising results could this out-compete other products and attract customers. This creates a pattern where products with ambitious sustainable goals get an EPD. Therefore, multiple EPDs describes an over average good environmental performance for special variations of products. This could affect the study's results, as the emission factor for materials might be lower than averages. A lower emission factor could make the results less realistic and better than the reality. It could be possible to assume that the new machinery would use the most sustainable products at the market, which would solve this problem.

The third problem is related to the parameters of the EPD. All impact is already calculated in an EPD, but these impacts will be based on specific parameters like location or lifetimes. If the EPD uses Germany as location will all transportation and electricity impacts be based on Germany. The emission factor for electricity would probably be higher, and the transportation would probably be different, compared to Norwegian production chains. To avoid the transportation problem, have emissions from transportation been removed from the emission factor. The material is rather assumed to be produced locally before being transported to the machinery production site. The electricity variation has not been considered in this study, as the European electricity mix is assumed to be like other European countries electricity mixes.

It is important to be aware of the challenges mentioned above, as they could make the results less trustworthy. The probable emission factors will differ from the ones taken from EPDs, and one could therefore discuss whether the EPDs should be used while assessing general products. The results could potentially be more accurate if a more general database with regional emission factors were used. However, this study has assumed that the uncertainty created by EPDs are low enough to still consider the results as trustworthy.

6.2.3 Substitution limitations

Substitution methods have both advantages and disadvantages. This is important to have in mind while assessing this study's result. Especially the disadvantages could make the result less accurate on less trustworthy. A couple of advantages and disadvantages will be enlightened.

One disadvantage is how the substitution method assumes that the by-product will replace another product. For example, when the fish sludge fertilizer replaced chemical fertilizers in this study. This might not always be the case but is a theoretical approach. The impact from producing the replaced product will be subtracted from the total emissions, regardless of whether the products production volume actually decreases because of the new byproduct utilization.

Another related disadvantage is the choice of replaced product. It is important to choose the replaced product carefully. If the byproduct should replace a product with lower environmental impact, the replacement would be bad. This was truly clear in the substitution for scenario 2, where the hydro power had much lower impact than the bioenergy production from sludge. Related to this will the person conducting the LCA decide which product will be replaced and can choose the product with highest environmental impact. In other words, choosing the product depending on the environmental impact, instead of how realistic the substitution is. This could make the LCA results seem better, but the results would be unlikely.

The previous disadvantages show how the replacement options are many, and that the choice will affect the results. This creates an uncertainty that occurs while trying to predict the likely changes. Therefore, it could often be a promising idea to perform a sensitivity analysis on the different technology alternatives for substitution. This was not done in this study because of the lack of time.

The last disadvantage is the framework. There is no formal framework for substitution, which means that different studies will use different approaches, concepts, or models. This could make the results from studies with similar research question and goal different. Without a formal framework could substitution be confusing and make the results more questionable for readers.

All these factors make the model transparency lower for LCAs with substitution. However, there is one large opportunity with the substitution method. This is the idea of using byproducts to replace another produced product. If the substitution is fair and realistic, the result could be a sustainable measure. An important part of sustainable food production is to use resources smarter. This means to see what resources available and not utilized today. The byproduct will be produced anyway and should be used instead of the traditional production. To reach environmental goals, there will be a need for new and smarter solutions to limit the populations resource use. Substitution could in practice be a method to achieve such solutions.

6.2.4 Data availability and reliability

This study has used minimal data given from Pronofa, while most data is generic values taken from research or industry. Most data are simplified within the limits of reason as well. For example, the drying machinery. Most machinery consists of electrical components and simpler parts, not just steel and plastic, as this study have described most machinery. If the study would be more detailed and specific could also emissions from transportation depend on the accessibility and climate for the traveling route. Including more specific details to the study will make the results more accurate, but also require more work. Probably much more work than the details will change the results.

There is one important disadvantage with the simplifications in drying machinery. The results were shown to be overly sensitive to changes in drying machinery. This means that that inaccuracies in this stage will create more uncertainties than other stages. For example, changes in the maintenance stage has less impact on the results, which means that inaccuracies are more affordable here. Therefore, the dewatering and drying machinery should be prioritized when it comes to detailed data.

The main sources of data were EPDs, research, data sheets, industry homepages, and vegLCA. EPDs, data sheets and vegLCA is considered at reliable sources. Previous research and industry homepages could be more problematic. Previous research could be irrelevant somehow, imprecise, or outdated. Using outdated research could be avoided by only using recently published research, but irrelevant and imprecise research could be harder to reveal. Industry homepages have no guarantee that all information is correct, as the main goal is to sell their products. The problem with data sheets is not the reliability, but to understand the product and the data, as this could be confusing. This study has assumed that the gathered date sheets and previous research could be transferred to the theoretical fish sludge production, but this could potentially be a bold assumption that leads to incorrect results.

6.2.5 Impact categories and characterization factors

In this study, only two impact categories were calculated. These two was global warming and eutrophication potential. Both categories could be placed in the ecosystem impact area of protection. Global warming could also be sorted into a human health category as well, but this was not done in this study, as ecosystem damage was in focus. When only assessing ecosystem damage from GWP and EP could other impacts be overlooked.

Some categories that potentially would be interesting to examine in this study would be the water consumption, acidification, toxicity and resource scarcity in general. The effect of more impact categories would probably capture more impact or address large impacts that were overlooked. One scenario could for instance have large acidification impact that would change the end results. This study has assumed that the impact in other categories is minor compared to the GWP and EP, and that the other impacts would be distributed equal between the scenarios. One of the main reasons to choose GWP and EP was that the different scenarios would have individual impact in these categories. This was important as all scenarios would be compared to each other and the base case.

The base case had large EP as suspected, while other scenarios had large GWP. The two impact categories made it possible to compare eutrophication impact in the base case with GHGs from sludge drying and utilization. Toxicity could be relevant if wastewater from fish breeding should leak 1.4-DBC-eq to the ecosystem around. At the same time, toxic emissions could be just as relevant in the production of materials. This means that comparison between base case and the other scenarios would be less interesting. On the other hand, fossil and mineral resource scarcity would probably be higher for the other scenarios than the base case, as the utilization require more resources. This makes resource scarcity more interesting to assess, but it could not be compared with the other impacts, as resource scarcity is a separate area of protection.

Only ecosystem damage has been assessed in this study. Resource scarcity and human health have not been included. Ecosystem damage was considered more suitable, as both GWP and EP could be compared in this area of protection. Ecosystem damage was also the area that answered the research question better. The studied system will still have impacts from GHGs in the human health category, and resource scarcity from fossil and mineral resources. It could be interesting to calculate this endpoint impact in DALY or USD2013, to potentially discover how the system affects other aspects of the environment. Even if scenario 1B seems to be the best for the ecosystem, it could for example be worse for the human health. This could be discovered if the study focused on more than the ecosystem impact. The results would in addition become more extensive.

The characterization factor will decide how significant impact GWP or EP will have on the different ecosystems. These factors have been taken from ReCiPe and are considered as the standard factors. Hierarchic factors were chosen for this study, as the middle road between individualist and egalitarian was assumed to be most realistic. The CF for GWP impact on freshwater was remarkably low, and significant higher for terrestrial ecosystems. This meant that the GWP had insignificant impact on the freshwater ecosystems compared to terrestrial ecosystems. In addition, the CF for EP in freshwater ecosystems had the highest value. This resulted in a total freshwater impact that was mostly affected by the P emissions, not the GWP. It could therefore be debated whether adding the impact from GWP to the freshwater have so insignificant effect on the results, that GWP could be neglected from freshwater ecosystems to save time. Adding the ecosystem impact of GWP on freshwater is a small detail with less importance in this study.

It is important to use trustworthy characterization factors, as this will weight which impact category that contributes with the most damage. For example, in this study did kg P-eq emissions weight more to the ecosystem damage than N-eq and CO_2-eq emissions. This could potentially have a substantial impact on the results and is an important aspect of the endpoint characterization. At midpoint, the damage is expressed as kg CO_2-eq for GWP, while EP in freshwater is expressed as kg P-eq. Even if the GWP got a larger value could the EP do more damage. This quantification of impact for each midpoint category will convert the impact to endpoint, where the damage could be compared. However, the conversion could create uncertainties when multiplying with the CF. The CF express an average impact 1 kg P-eq or CO_2-eq does in the ecosystem, but this could vary from depending on situation or region.

It could be discussed whether species per year is a metric that communicate the impact well. This metric explains the expected number of extinct species due the environmental impact. Metrics as kg CO_2-eq or kg P-eq could be experienced as more tangible, while species.year is more diffuse. At the same time, extinction of species is much easier to imagine than 1 kg CO_2-eq, which could make species per year easier to communicate. Also, the metric would consider all species equally important, whether it is an insect or a mammal. This could seem strange for someone.

Note that the CFs are not regionalized in this study. This means that the factors are not specific to the area or country where the impact happens. Such regionalization is important to limit the spatial uncertainties in an LCA. This concept could be explained with an example for water use. The impact from water use will be less in Norway, where water is easily accessible, while the impact from water use could be much higher for African countries with water shortage. This explains how impact from a stressor will vary depending on the ecosystem current ecosystem. Some ecosystems are more sensitive to some impacts than others. When global CFs have been used, the impact could potential be over- or underestimated for the specific region. Regional CFs were not used in this study to simplify the calculations. When the different impacts happened in a wide range of locations, there would be a wide range of CFs for each location. This choice has led to more uncertainties in the results, which should be considered while viewing the results.

6.3 Improvements and future studies

The uncertainties should be improved in future similar studies. These uncertainties are mentioned above, and fixing these could make the results more accurate. Recommended improvements are presented in this chapter. The last section will in addition present interesting views and aspects that could be assessed in future studies.

At first could the level of details be improved. Especially the dewatering and drying machinery, scenario specific requirements and the transportation should be more detailed. This means to include more materials in machinery, more specific weights for each material, and specific assembly energy. For the transportation could infrastructure and vehicle manufacturing be included. Including these details will make the results more accurate.

Secondly, decisions should be made considering the parameters that effected the results the most. This is emission factors with recycling, emission factors for fuels, and the distribution of emissions from drying machinery. It should be reviewed whether the recycling is realistic, and if the lifetime factor seems fair. In addition, the data should be more specific to the real-life situations instead of a theoretical situation. This includes among other things the breeding facility location and produced fish sludge volume.

It could be interesting to expand the comprehensiveness in further studies. For starters, by including fish sludge collection from sea-based breeding. As mentioned earlier, the eutrophication potential should be significant larger from sea-based fish breeding. Assessing sea-based fish breeding would give the utilization much lower impact compared to the base case scenario. Sludge from land-based facilities is easier to study, as the facilities are obligated to collect the sludge today. However, it could be more important to uncover the impact from sea-based facilities compared to utilization scenarios.

Other interesting changes could be to implement another type of dewatering and drying machinery. The machinery could potentially be smaller with reduced environmental impact, as this could be more realistic. If else, the study could be conducted with the concept of sharing one common drying machinery. Also, the scope could be broadened to include the BSF breeding. Then the final product from fertilizing, BSF's and energy consumption could be compared. This could potentially give more useful results for specific situation.

6.4 Recommendations

This study has obtained an overview of sustainable fish sludge utilization. After examining the results, a couple of recommendations have been formulated. This could be considered by the fish breeding industry, insect breeding industry, or the government.

The food safety aspect of fish sludge has not been assessed in this study, only the ecosystem impact aspect. From an environmental view is fish sludge recommended for utilization within the energy, insect breeding and agriculture sector. The utilization will prevent significant ecosystem impact from the breeding facilities and production of alternative products. Therefore, it would be more sustainable to change today's regulations for fish sludge utilization, as a promising resource will go to waste. Also, using fish sludge as BSF substrate is recommended, as this has large environmental benefits. If the sludge will be dried, it is recommended to keep the environmental impact from drying machinery in mind. Down scaling the machinery, sharing machinery between multiple facilities, using electricity with lower emissions, or recycling materials would decrease the impact from drying.

7 Conclusion

The research question of this study was:

What is the environmental impact of utilizing fish sludge as a substrate for black soldier fly, and is it environmentally beneficial compared to other utilization options?

The research question could be answered with the results provided in this LCA. Results presented in this study could be used for the fish industry, insect breeding industry, or organic fertilizer industry while deciding whether using fish sludge in their production. It could also be used while assessing new regulations for fish sludge utilization.

Data from EPD's, data sheets, ReCiPe2016, and vegLCA have been used for the calculations in Excel. The LCA was conducted with multiple scenarios, options for different parameters and substitution.

The scenario where dry sludge was used as black soldier fly substrate had an ecosystem impact at $-3.24 * 10^{-4}$ species.year, while utilization of wet sludge for black soldier fly had an impact at $-3.66 * 10^{-4}$. Dry sludge for bioenergy production had an ecosystem impact at $9.49 * 10^{-5}$ species.year. The scenario where dry sludge were used as fertilizer had an impact at $-2.05 * 10^{-5}$ species.year, while wet sludge had an impact at $1.18 * 10^{-5}$. The base case where the sludge was not utilized had an impact at $7.65 * 10^{-4}$ species.year. These results were calculated with Norwegian electricity mix and diesel as transportation fuel.

The ecosystem impact was significant lower for scenario 1A and 1B, as the impact from transportation and processing of sludge for black soldier fly was low. The drying machinery contributed to most emissions in scenario 1A, mostly because of the high consumption of energy and steel. The base case, where the sludge was not utilized, had higher emissions than all utilization scenarios, as the phosphorus emissions had significant impact on the ecosystem. To conclude, all utilization options were more environmental beneficial than not utilizing the fish sludge, and the black soldier fly scenario had least ecosystem impact.

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A Appendix

A.1 Figures

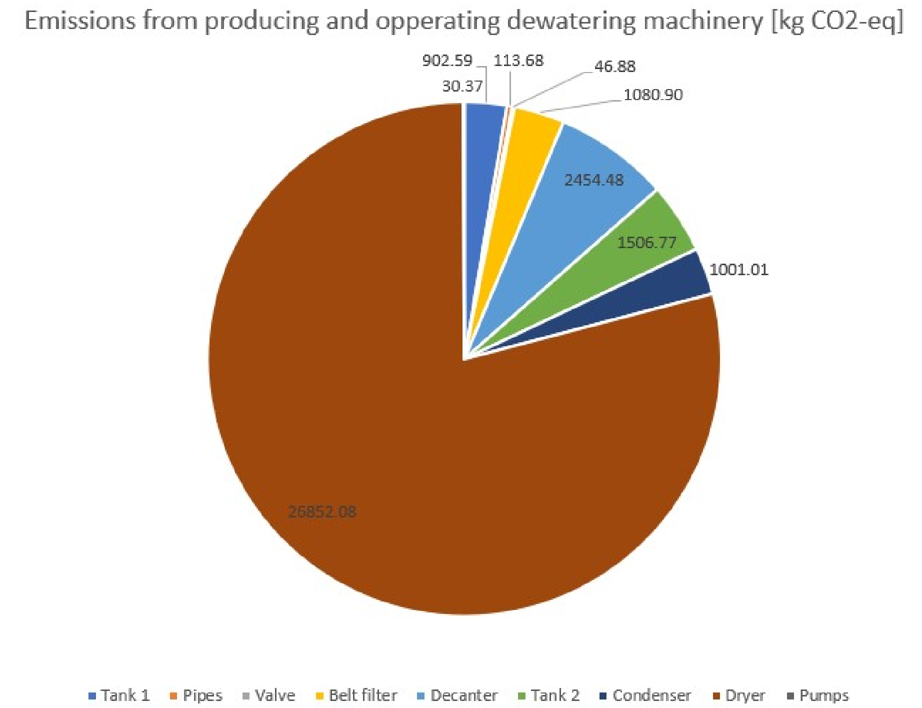


Figure A.1: GWP from producing materials, transporting materials, and operation of the machinery for dewatering in kg-CO_2-eq.

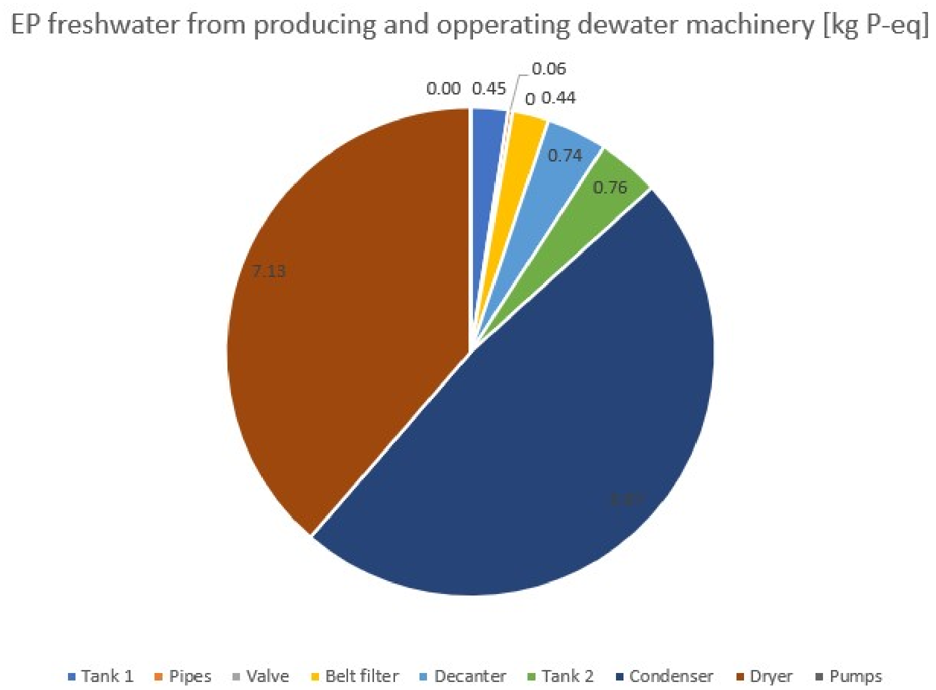


Figure A.2: Freshwater EP from producing materials, transporting materials, and operation of the machinery for dewatering in kg P-eq.

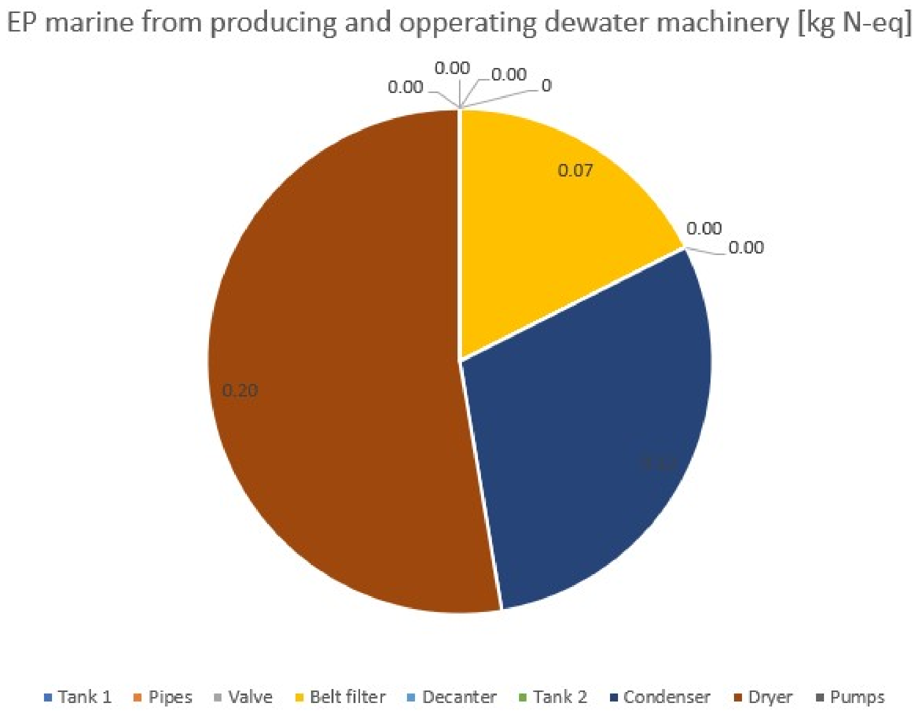


Figure A.3: Marine EP from producing materials, transporting materials, and operation of the machinery for dewatering in kg N-eq.

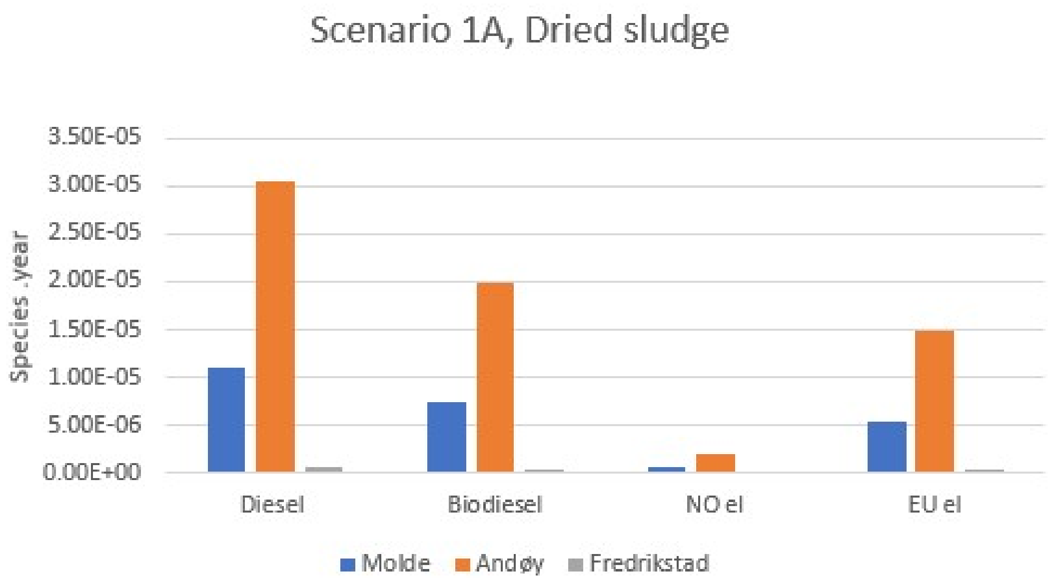


Figure A.4: Comparison of the ecosystem impact [species.year] for the different fuels options, when the sludge is dried in scenario 1

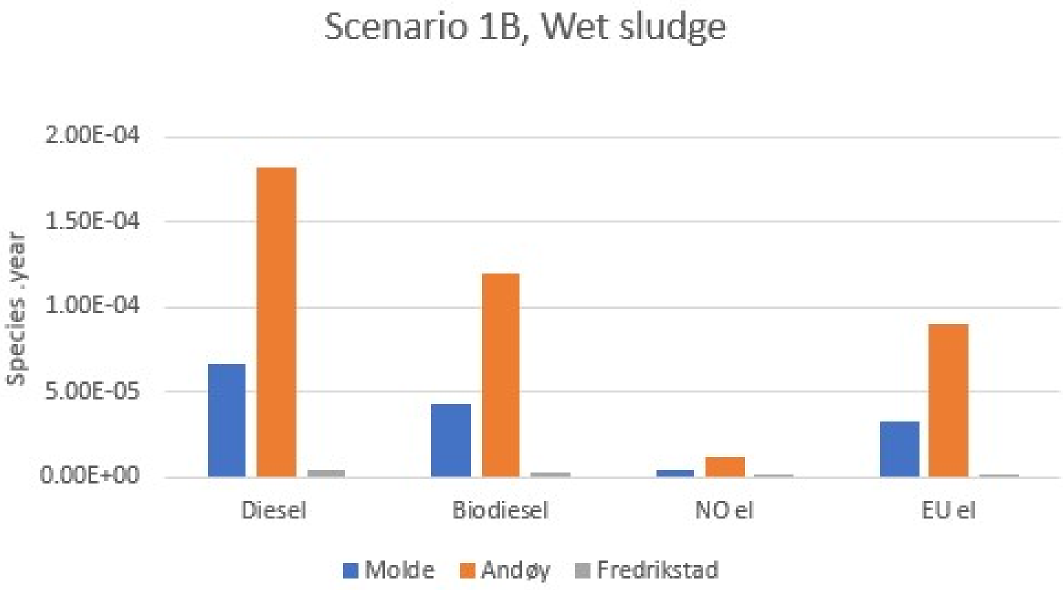


Figure A.5: Comparison of the ecosystem impact [species.year] for the different fuels options, when the sludge is wet in scenario 1

Impact	Freshwater	Marine	Terrestrial	Unit
NO el	$1.42 * 10^{-7}$	$2.6 * 10^{-10}$	$3.23 * 10^{-6}$	species.year
EU el	$1.42 * 10^{-7}$	$2.6 * 10^{-10}$	$3.3 * 10^{-6}$	species.year

Table A.1: Endpoint impact from utilization specific requirements in scenario 1

Impact	Freshwater	Marine	Terrestrial	Unit
NO el	$7.96 * 10^{-8}$	$2.26 * 10^{-10}$	$2.99 * 10^{-6}$	species.year
EU el	$8.00 * 10^{-8}$	$2.26 * 10^{-10}$	$1.63 * 10^{-5}$	species.year

Table A.2: Endpoint impact from utilization specific requirements in scenario 2

Impact	Freshwater	Marine	Terrestrial	Unit
NO el	$1.29 * 10^{-10}$	0.00	$6.38 * 10^{-9}$	species.year
EU el	$1.49 * 10^{-10}$	0.00	$6.40 * 10^{-9}$	species.year

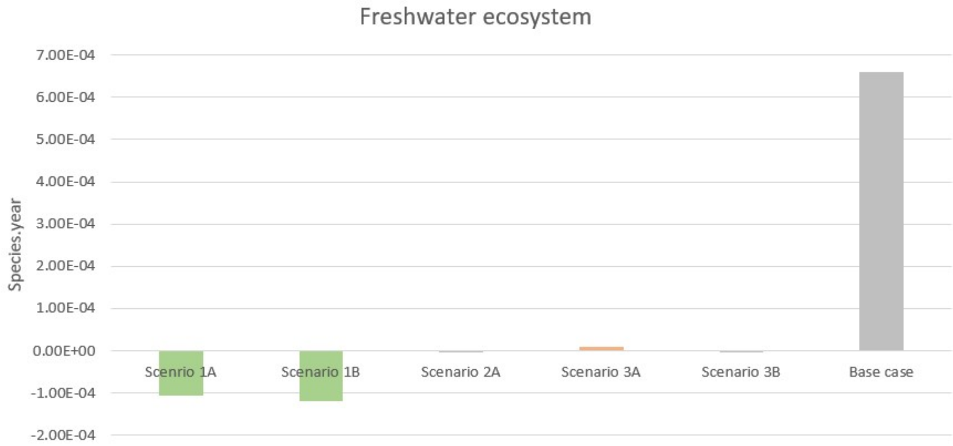
Table A.3: Endpoint impact from utilization specific requirements in scenario 3A

Impact	EP freshwater	EP marine	GWP	Unit
NO el	$7.04 * 10^{-7}$	0.00	$9.07 * 10^{-6}$	species.year
EU el	$7.04 * 10^{-7}$	0.00	$6.43 * 10^{-5}$	species.year

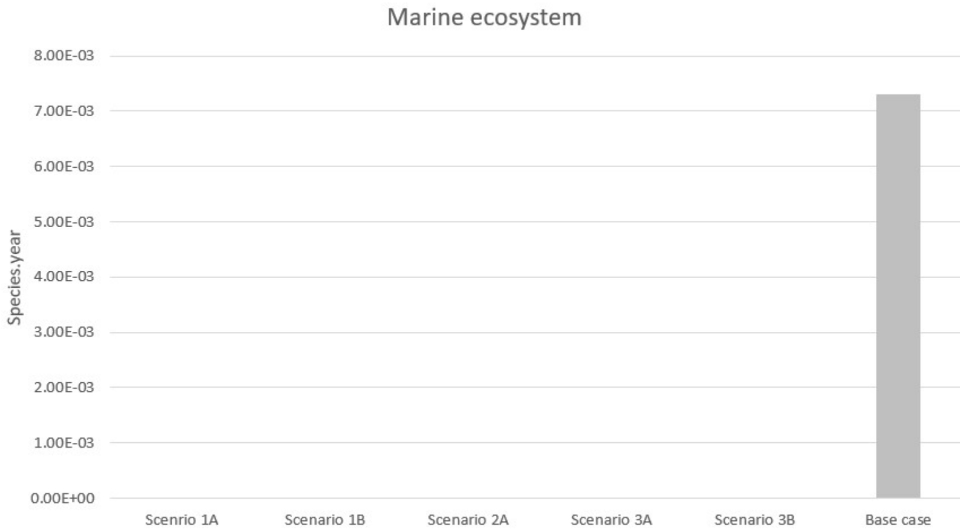
Table A.4: Endpoint impact from utilization specific requirements in scenario 3B

Sceanrio	kg P-eq	kg N-eq	kg CO_2-eq
1A	$1.87 * 10^{1}$	$4.91 * 10^{-1}$	$3.48 * 10^{4}$
1B	$7.78 * 10^{-1}$	$1.04 * 10^{-1}$	$2.87 * 10^{3}$
2A	$1.86 * 10^{1}$	$5.2 * 10^{-1}$	$3.51 * 10^{4}$
3A	$1.95 * 10^{1}$	$3.87 * 10^{-1}$	$4.38 * 10^{4}$
3B	$2.80 * 10^{0}$	$0.00 * 10^{0}$	$1.51 * 10^{4}$
Base Case	$9.82 * 10^{2}$	$1.09 * 10^{4}$	$3.75 * 10^{4}$

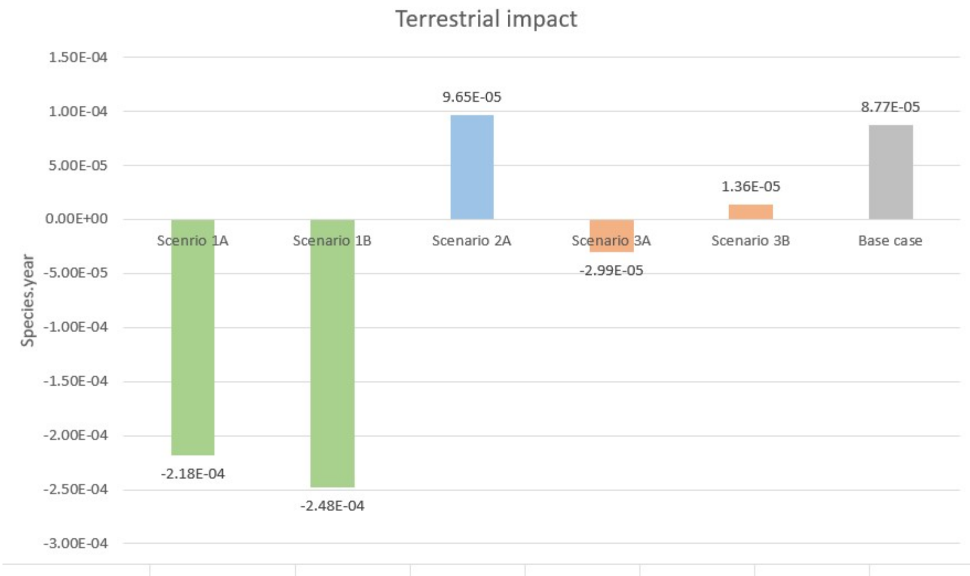
Table A.5: P-eq, N-eq and CO_2-eq emissions in the different scenarios without substitution



((a)) Freshwater ecosystems



((b)) Marine ecosystems



((c)) Terrestrial ecosystems

Figure A.6: Impact on freshwater, marine and terrestrial ecosystems from all scenarios in species.year

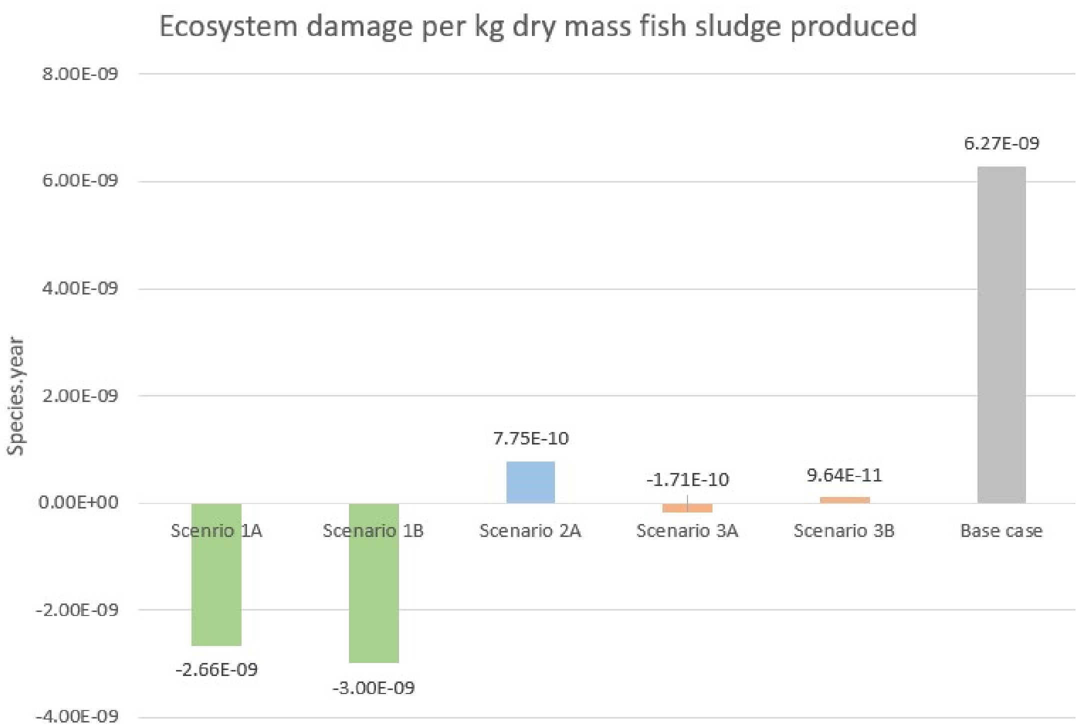


Figure A.7: Total ecosystem impact in species.year per kg fish sludge in dry mass

A.2 Cylinder volume for pipes and tanks

$$V = \Pi * r^2 * h \tag{A.1}$$

Where r is the radius and h the height.

NTNU
Norwegian University of
Science and Technology