MASTER'S THESIS ACEX30

Environmental impacts of alternative water treatment strategies of process water from a herring processing plant

Work in collaboration with Scandic Pelagic, RISE Agriculture and Food and Chalmers University of Technology

Master Thesis in the Master Programme Industrial Ecology

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Göteborg, Sweden 2020

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ABSTRACT

Throughout human existence, the oceans have been used as recipient for residues of man's activities, which is still causing great environmental damages on the marine environment. Today, eutrophication of coastal areas is one of the most difficult environmental challenges humans are facing and the gradual increase of eutrophying emissions to the oceans shows the importance of creating and using sustainable solutions in order to mitigate as much emissions as possible. Hence, stricter legislations and requirements regarding wastewater treatment have been implemented as a strategy to reduce eutrophication. In Sweden, the Swedish herring company Scandic Pelagic AB (owned by the Danish company Skagen FF) have since the 1990's rented part of the WWTP of the municipality in Orust, north of Göteborg for treatment of industrial wastewater. However, due to new emission requirements they are only allowed to use this solution until the end of 2021, meaning that Scandic Pelagic needs to find another solution for their wastewater treatment.

The goal of this work was to compare the environmental impacts of the current wastewater treatment with a number of proposed alternative solutions using a life cycle assessment (LCA). The environmental categories global warming (kg CO_2-eq) and eutrophication (kg N-eq) were considered. The goal was also to compare the removal efficiencies of organic matter and nutrients (BOD, N and P). The assessed alternatives are: Scandic Plagics' current WWTP; pre-treatment plant + mussel farm, using boat for transporting process water to mussel farm; pre-treatment plant + mussel farm, using pipelines for transporting process water to mussel farm; pre-treatment plant + MBBR technology; pre-treatment plant + SBR technology; and pre-treatment plant + SBR technology + surge tank.

The results showed that the alternative pre-treatment plant + mussel farm (boat) has the highest global warming and eutrophication impact (132kg CO_2-eq and 0.013kg N-eq) and the lowest contributor is pre-treatment plant + SBR (61kg CO_2-eq resp 0.0016kg N-eq). Pre-treatment plant + MBBR was the highest emission contributor (89kg CO_2-eq resp 0.024kg N-eq) among the assessed WWTPs mainly operated on land but has the highest nutrient reduction capacity. A correlation of the nutrient and organic removal efficiency levels and the environmental impact of the assessed alternatives could be observed. Since this work indicated that an increase of chemical, energy and material use generate a greater reduction of organic matter and nutrients in process water. Based on this LCA study, pre-treatment plant + SBR should be implemented as a future solution by Scandic Pelagic since this is the most environmentally friendly treatment method and at the same time has sufficient organics removal.

Miljöeffekterna för processvatten av alternativa metoder for vattenrening från ett sillberedningsföretag

Examensarbete inom mastersprogrammet Industriell ekologi

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SAMMANFATTNING

Under människans existens har havet använts som recipient för mänsklig aktivitet vilket på långt sikt orsakat stora miljöskador på den marina miljön. I dag är övergödning av kustområden en av de svåraste miljöutmaningarna som människor står inför och den gradvisa ökningen av övergödningsämnen i haven indikerar nödvändigheten av att skapa och använda hållbara lösningar för att minska så mycket utsläpp som möjligt. Därmed har också en strängare lagstiftning och krav implementerats gällande behandling av avloppsvatten som en strategi för att minska övergödning i haven. I Orust, Göteborg driver det svenska sillberedningsföretaget Scandic Pelagic AB sin verksamhet (som ägs utav det danska företaget Skagen FF) och har sedan 1990-talet hyrt en del av kommunens avloppsreningsverk för behandling av industriellt processvatten. Dock har samarbetet mellan parterna upphörts p.g.a nya reningskrav och Scandic Pelagic får endast använda denna lösning fram till slutet av 2021, vilket innebär att Scandic Pelagic behöver hitta en annan lösning för deras processvatten.

Målet med detta arbete var att jämföra miljökonsekvenserna av den nuvarande avloppsreningen med ett antal föreslagna alternativa lösningar med hjälp av en livscykelanalys (LCA) baserat på miljöeffekterna; global uppvärmning (kg CO_2-ekv) och eutrofiering (kg N-ekv). Målet var också att jämföra reduceringseffektiviteten av organiskt material och näringsämnen (BOD, N och P). De utvärderade alternativen är: Scandic Plagics nuvarande WWTP; förbehandlingsanläggning + musslingodling, med båt för transport av processvatten till musslingsodling; förbehandlingsanläggning + musslingodling, med hjälp av rörledningar för transport av processvatten till musslingsodling; förbehandlingsanläggning + MBBR-teknik; förbehandlingsanläggning + SBR-teknik; och förbehandlingsanläggning + SBR-teknik + överspänningstank.

Resultaten visade att förbehandlingsanläggningen + musslingodling (båt) har den högsta globala uppvärmnings- och övergödningspåverkan (132 kg CO_2-ekv and 0,013 kg N-ekv.) Den lägsta bidragsgivaren är förbehandlingsanläggningen + SBR (61 kg CO_2-ekv resp 0,0016 kg N-ekv). Förbehandlingsanläggning + MBBR var den högsta utsläppsgivaren (89 kg CO_2-ekv. resp. 0,024 kg N-ekv.) bland de utvärderade WWTP-alternativ som huvudsakligen drivs på land men har den högsta näringsreduceringseffektivitet. En korrelation mellan avlägsnande av näringsämnen och organiskt material och miljöeffekterna av de utvärderade alternativen kunde observeras. Då resultaten indikerade att en ökning av kemisk, energi och materialanvändning genererar en större

reduktion av organiskt material och näringsämnen i processvatten. Baserat på denna LCA-studie bör förbehandlingsanläggning + SBR implementeras som en framtida lösning av Scandic Pelagic eftersom detta är den mest miljövänliga behandlingsmetoden och en tillräcklig reducering av organiska ämnen.

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Preface

The report is the outcome of the master's program Industrial Ecology at Chalmers University of Technology. Stakeholders involvement for this thesis is Scandic Pelagic AB, RISE Agriculture and Food and Chalmers University of Technology.

The supervisor of this master thesis is senior scientist Friederike Ziegler at RISE Agriculture and Food and examiner is Oskar Modin, professor at Chalmers University of Technology. This work is a collaboration with Scandic Pelagic, RISE Agriculture and Food and Chalmers University of Technology.

Göteborg May 2020

Caroline Huynh

Abbreviations

BAT - Best available technology

BOD - Biochemical oxygen demand

CO_2 eq - Carbon dioxide equivalents

COD - Chemical oxygen demand

EU - Eutrophication

EP - Eutrophication potential

FU - Functional unit

GW - Global warming

GWP - Global warming potential

IC - Impact categories

LCA - Life cycle assessment

LCI - Life cycle inventory

LCIA - Life cycle impact assessment

MBR - Membrane bio reactor

MBBR - Moving bed bio reactor

N - Nitrogen

N eq - Nitrogen equivalents

P - Phosphorous

SBR - Sequencing batch reactor

SP - Scandic Pelagic

WW - Wastewater

WWT - Waste water treatment

WWTP - Waste water treatment plant

1 Background

1.1 The marine environment

For many years, the oceans have been used as a recipient for mans' activity which has led to negative changes and affected the marine environment worldwide. The Swedish marine environment is therefore a highly discussed topic and an on-going debate, since it is included in several goals of the Swedish 16 environmental quality objectives (*Sveriges miljömål*, 2017). At the same time, the EU has during the recent years restricted the requirements in order to increase the marine protection and reduce emissions of pollutants. To maintain a good and sustainable marine environment, the seas shall be protected and preserved accordingly to the requirements of the Marine Directives (incorporated into the Swedish legislation in 2010), which follows the content of the EU Directive. The requirements of the Swedish Marine Directives are aimed at a level to reduce pollution and prevent harmful substances to cause environmental damages and thereby improving the condition of water living animals, plants and organisms (*Havs- och vattenförvaltningen - Svenskt Vatten*, 2016). Hence, stricter emission requirements have been set for wastewater treatment plants throughout the country and due to the circumstances may affect multiple companies with own wastewater treatment plants as well (Åmand *et al.*, 2016).

Emissions of eutrophying substances from the municipal wastewater plants is currently the second largest sector contributing to eutrophication in Sweden. Therefore, it is highly important to restrict the emission levels to protect the seas.

1.2 The Swedish Environmental Code - General requirements and permission of wastewater treatment plants

The Environmental Code (SFS 1998:808) aims to promote sustainable development for current and future generations. The law affects all industries, as the legislation applies to all activities that affect the environment. This implies that companies shall gather enough information and knowledge but also use the best available technology (BAT) in order to avoid any environmental damages and protect humans as well (*Minska företagets utsläpp av miljögifter - Svenskt vatten*, 2012). The Environmental Code also introduced the environmental quality standards (EQS), meaning that the technology in any respect, is not allowed to deteriorate the current marine status. In other words, no parameters are allowed to get deteriorated even if multiple parameters would be improved. The implementations made by the EU Framework Directive and the Swedish marine legislations have thereby affected the conditions for discharging wastewater (*Miljökvalitetsnormer för vatten - Svenskt Vatten*, 2020).

Furthermore, companies who are applying for permit of emitting process water to the treatment plant of the municipality must, according to the law (Lagen om allmänna vattentjänster, SFS 2006:412), receive a permission by the municipality (VA-huvudmannen). However, the municipality are not obligated to receive any process water from companies (VA-abonnenten) that is not considered treatable. If the company is aiming to run an own wastewater treatment plant (>2000 pe), they need to apply for permission from the environmental standards inspectors. According to the Environmental Code, the permits shall contain several conditions, such as emission levels, limit values and best available technology (BAT) from an environmental point of view shall be used (Svenskt Vatten, 2013).

1.3 Short review of life cycle assessment (LCA)

The ISO (14040:2006) standard of life cycle assessment (LCA), describes the LCA framework and procedure for assessing environmental impacts of a product or service. The approach implies that a product is followed from raw material to its service or disposal, also referred as either "cradle to gate" or "cradle to grave". The strength of using the LCA methodology is that it is able to study the whole life cycle, but at the same time a drawback is that it is not site specific. Hence, the LCA methodology cannot study the environmental impacts at every detailed level. An important factor to keep in mind is that it does not assess any economic or social aspects as well (Tillman and Baumann, 2004).

The main components of a life cycle assessment procedure are defining a goal and scope, inventory analysis, impact assessment and interpretation of the study. In addition, a **functional unit (FU)** must be selected in order to accomplish a comparison between different system. The functional is used to quantify the function of a product which all assessed flows relate to. The FU is independent from the production or the consumption volumes. A product can have multiple functional units but is selected depending on the purpose of the LCA-study. LCA studies are then able to summarize the environmental issues of the product into categories, also referred to as **impact categories (IC)** (Muralikrishna and Manickam, 2017). In LCA, the system has to be limited in multiple dimensions e.g. geographically, these limitations are set in the **system boundaries**. **Allocation** can be defined as partitioning the input or output flow of a process to the product system under study (ISO 14040 1997). This procedure is used to correctly quantify the environmental impact of multiple outputs.

1.4 Previous LCA studies on environmental impacts from wastewater treatment plants

During recent years, several LCA studies have been conducted regarding a correlation between WWTPs' removal efficiency levels and emissions and significant correlations could be observed. Foley et al (2009) were studying several WWTPs (mainly sedimentation and sludge treatment plants) and the selected functional unit (FU) was 1 m^3 treated wastewater. They could conclude that an increasing removal efficiency level of organic matter (especially nitrogen) would generate increased greenhouse gas (GHG) emissions. The observed result was mainly due to higher energy, material and chemical consumption for the assessed WWTPs. However, the researchers could hardly find any correlation between increased removal efficiency of phosphorus and environmental impacts. This study did only include the largest share of material use for the assessed WWTPs, which was concrete (Foley *et al.*, 2009).

In 2011, another LCA study could report a very similar result. The assessment was evaluating 24 different WWTPs in Brazil, using Global Warming Potential (GWP) and Eutrophication Potential (EP) as environmental impact indicators. The selected functional unit (FU) was 1 m^3 treated wastewater. Similar to previous LCA report, the authors could observe that the WWTPs with a significant higher energy consumption for obtaining a higher quality of effluent, did overall generated increased emissions but lower eutrophication since higher nutrients efficiency was achieved, compared to smaller WWTPs with lower removal efficiency level of organic matter. The researchers further indicated a correlation of the nutrient removal efficiency, global warming and eutrophication in their results. For this case study, the WWTPs' material construction, energy and chemical use were included for the evaluation (Rodriguez-Garcia *et al.*, 2011).

Over the last decade, the reduction efficiency level of organic matter (BOD) and phosphorous of municipality wastewater treatment plants in Sweden is approximately at 95% resp 90-95%. However, the reduction efficiency level of nitrogen is significantly lower as the average reduction level is currently approximately at 60-70%. Yet, these values are gradually improved with better technologies and knowledge (Naturvårdsverket, 2012b) (*Svenskt Vatten*, 2018)

When comparing the removal efficiency to other municipality wastewater treatment plants outside of Europe, similar levels can be observed. In China, the average removal efficiency of organic matter (BOD) is approximately at a level of (91% ± 6.7%), phosphorous at (80.8 ± 11.8%) and for nitrogen at (65.5 ± 13.9%.). These values are strongly similar to developed countries as best available technology (BAT) is mainly used and in general stricter environmental policies (Qi *et al.*, 2020). Since the municipality of wastewater treatment plants in developing countries do not have any legal reference documents for BAT, a lower removal efficiency level can be expected. In 2013, UNICEF could report that 70% of urban India's sewage do not undergo any treatment, thereby showing the contrast between developed and developing countries. As developed countries don't have the same opportunities, the public health and marine environment are constantly in jeopardize (Starkl *et al.*, 2018).

1.5 Scandic Pelagic AB

Scandic Pelagic AB is a Swedish fish company (owned by the Danish company Skagen FF) and specialized in processing of Atlantic herring (*Clupea harengus*) and today one of the world's leading producers of marinated herring products. The herring is mainly caught in Kattegatt, Skagerak and Nordsjön before it is transported to the facilities for processing/preservation. The company is currently located in Skagen and Ålbæk (Denmark) and in Ellös, Västervik and Gotland (Sweden). Their products are based on herring, but sprat (bristling or brisling) products are another important species and product group for the company where these are caught and unloaded on the operation facilities (*Scandic Pelagic*, 2019). S.P in Ellös is producing about 83ton herring products per production day, resulting into an amount of nearly 10000ton herring annually. The production results in approximately 55000m^3 of industrial process water annually undergoing several wastewater treatments steps before being emitted to the recipient ("Scandic Pelagic - samrådsunderlag," 2020). Part of the operation facility in Ellös can be seen in figure 1.

Figure 1. Part of S.Ps' operation facility in Ellös (Photos by Caroline Huynh, 2/3-2020).

Since the 90's, S.P has rented a part of wastewater treatment plant of the municipal in Orust, called Ellös ARV, for the final treatment of industrial process water before it is transported to the recipient. A detailed description of the location of Ellös ARV and the operation facility in Orust can be further observed in figure 2.

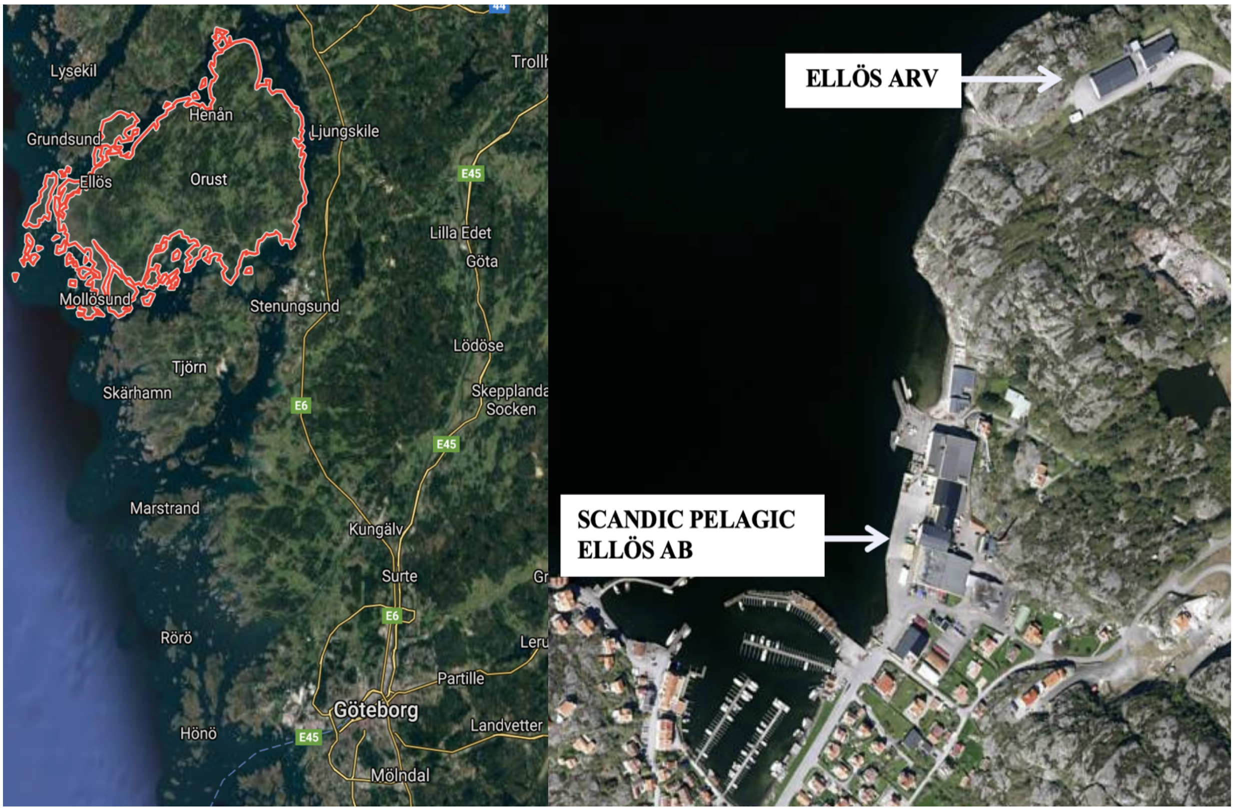

Figure 2. The location of Scandic Pelagic Ellös AB and Ellös ARV in Orust (*Google Maps*, 2020).

The industrial process water from the facility contains organic material and different nutrients mainly from scales, blood and intestinal content from the fish. Although the process water has only been in contact with fresh fish caught from the sea, the water still needs to be treated before it can flow out to the recipient again. This is due to the water being defined as industrial process water and if the water does not undergo any treatment process, this would be considered as dumping of waste and according to the Swedish law (Lag (1971:1154) om förbud mot dumpning av avfall i vatten) strictly forbidden (*Dumpning - Havs- och vattenmyndigheten*, 2018) (*Lag (1971:1154) om förbud mot dumpning av avfall i vatten Svensk författningssamling 1971:1971:1154 t.o.m. SFS 1998:376 - Riksdagen*, 1998).

1.6 The current situation

Since the 90's, S.P has collaborated with the municipality for treatment of industrial process water from the manufacturing process of S.P. The operation facility is currently using a pre-treatment plant (owned by the company) but this is not sufficient to fulfil the emission requirements. Hence, part of the municipality treatment plant in Orust, called Ellös ARV, is therefore rented by S.P in which the primary pre-treated process water undergoes a second treatment before it is released to Ellösfjorden.

However, the county government of Gothenburg has demanded a higher degree of nitrogen reduction of the municipality, resulting in a decision to build an entirely new municipal wastewater treatment plant that will replace all existing plants in Orust. Hence, the municipality has decided to end the collaboration agreement with S.P. This means that S.P must re-build their current wastewater treatment plant in order to meet the new emission requirements. According to the new agreement, the pre-treated industrial process water from S.P can no longer be treated in Ellös ARV after 2022-01-01. As mentioned, a process of a new permit for wastewater treatment plant is now under process and according to plan, the new treatment plant must be finished and be able to run in 2022-01-01 as well.

Due to the circumstances, S.P has contacted several stakeholders in order to evaluate how the situation should be managed for achieving a potential solution. The developing process is very time limited and a several proposals have been suggested as possible solutions for S.P but these needs to be evaluated before any decision making ("Scandic Pelagic - samrådsunderlag," 2020)

1.7 Description of Scandic Pelagics' current pre-treatment process of industrial process water

The process water is first collected into a well and then pumped to a washer belt for removal of the very largest particles. The water is then treated in a drum filter in order to remove further bigger particles (> 78 µm). Using a conveyor belt, the removed particles are collected and transported to tanks for further use as fish oil.

The remaining water flows on to a flotation where different chemical compounds (hydrochloric acid, lye and poly-aluminum chloride) are added into the water in order to precipitate e.g. fat and proteins. The remaining sludge and treated water are then separated, and the sludge is used for biogas production and the pre-treated water flows on to Ellös ARV for a final treatment before it ends up in the recipient, Ellösefjorden. However, the current pre-treatment process is not efficient enough considering the new emission requirements. A new WWT alternative solution for treatment of process water for S.P must therefore be found. ("Scandic Pelagic - samrådsunderlag," 2020).

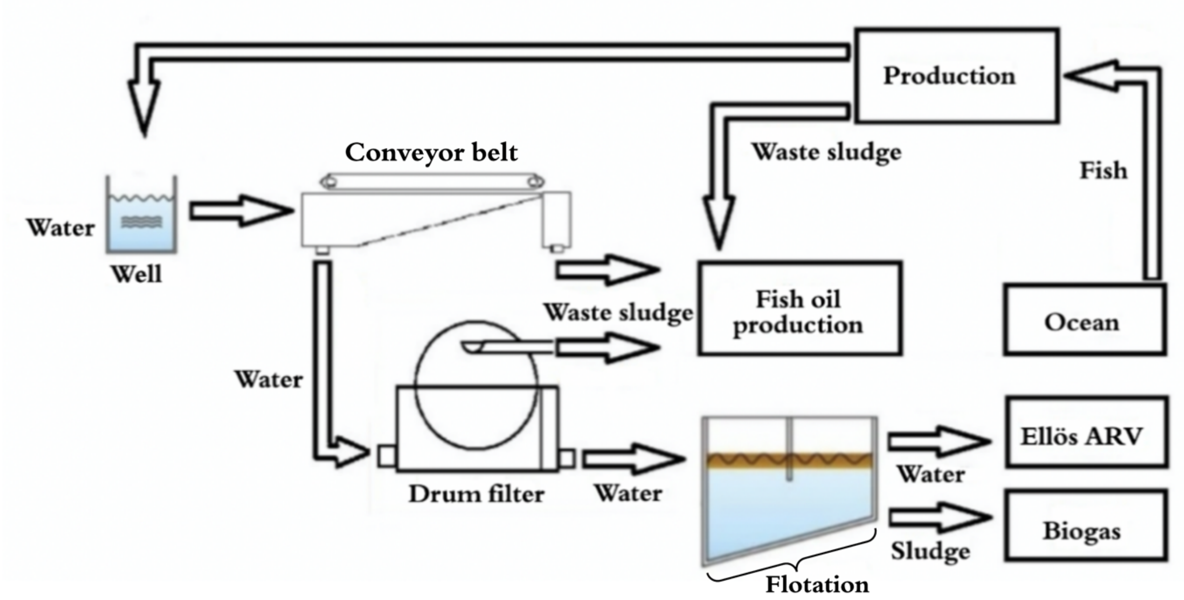

Figure 3. Scandic Pelagics' current pre-treatment process in Ellös, Orust (adapted from ("Scandic Pelagic - samrådsunderlag," 2020).

1.7.1 The potential solutions for Scandic Pelagic

S.P has concluded that the issue should be handled and solved accordingly to one of the treated alternatives presented in table 1.

Table 1. All proposed alternatives for S.P.

All proposed alternatives
1a) An additional flotation tank, using pipelines for disposal to mussel farms.
1b) An additional flotation tank, using boats for disposal to mussel farms.
1c) An additional flotation tank, using pipelines to recipient.
1d) An additional flotation tank, using boats to recipient.
2) An additional flotation tank + MBBR technology + sedimentation tank, using pipelines for disposal to the recipient.
3) An additional flotation tank + the SBR technology, using pipelines for disposal to recipient.
3*) An additional flotation tank + the SBR technology + surge tank, using pipelines for disposal to recipient.
4) The Membrane bio reactor (MBR)
5a) An additional flotation tank + (small) MBBR technology, using pipelines for disposal to mussel farms.
5b) An additional flotation tank + (small) MBBR technology, using boats for disposal to mussel farms.

2 Purpose of the research

The goal and purpose of this report is to assess the environmental impacts of Scandic Pelagics' current wastewater treatment plant and the proposed alternatives for treatment of process water using the LCA methodology.

Furthermore, a goal is also to compare the removal efficiency levels of organic matter (BOD) and nutrients (N and P).

3 Materials and methods

This chapter will present the how the methodology procedure was conducted for this report. Furthermore, presents how, and which methods were used, which treated alternatives were evaluated, how calculations based on both theoretical and empirical data were used in order to conduct an environmental assessment of the current one and the proposed alternatives.

3.1 Presentation of the alternatives assessed for this work

The presented options (see table 2) are the ones that were evaluated and assessed for this work, although other several alternatives have been proposed as well. A detailed case description of the alternatives 0-3, can be found in section 3.2.

Table 2. The assessed alternatives for this work.

0) S.Ps' current WWTP
1a) An additional flotation tank, using pipelines for disposal to mussel farms.
1b) An additional flotation tank, using boats for disposal to mussel farms.
2) An additional flotation tank + MBBR technology + sedimentation tank, using pipelines for disposal to the recipient.
3) An additional flotation tank + the SBR technology, using pipelines for disposal to recipient.
3*) An additional flotation tank + the SBR technology + surge tank, using pipelines for disposal to recipient.

3.2 Description of proposed alternatives

3.2.1 Alternative 1: An additional flotation tank in combination with mussel farms - Return of process water to the ocean as nutritional feed for mussel farming

Description of the new wastewater treatment plant: An additional flotation tank

S.P shall rebuild their current treatment plant by building an additional flotation tank, which will be placed between the drum filter and the already existing flotation tank. The plan is to not use any chemicals in the new additional flotation tank and the sludge will instead, after dewatering, be returned to the scrap tanks and be further used for fish oil production.

After treatment in the primary flotation tank, the process water will continue to the second flotation tank where flocculant, polymer and pH regulator are added before disposal of treated process water. The excess sludge will be used for biogas and the treated water is transported to the recipient ("Scandic Pelagic - samrådsunderlag," 2020).

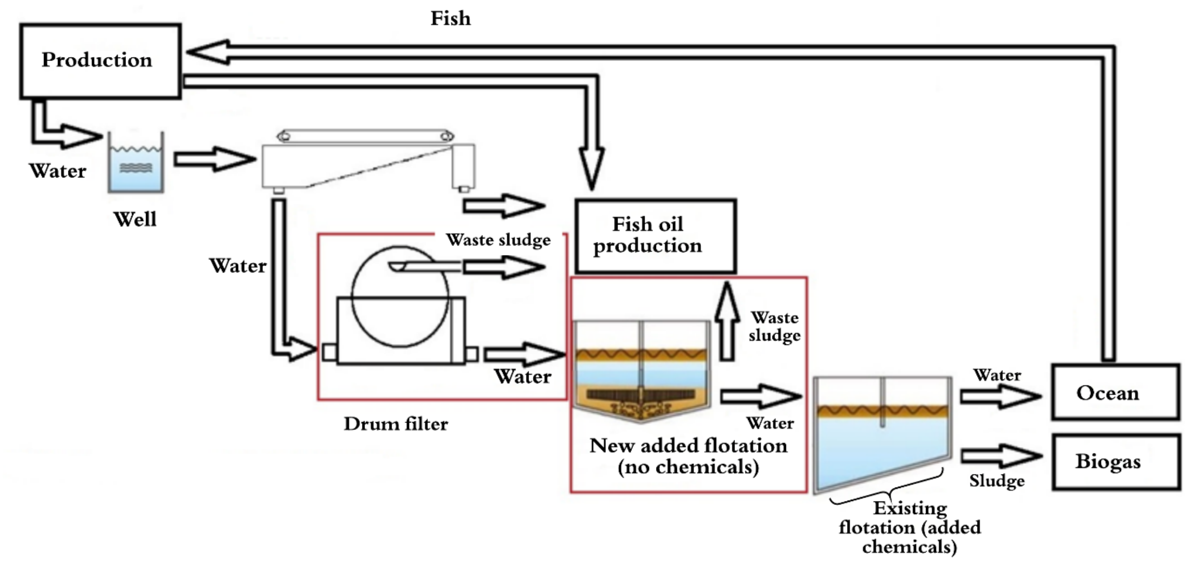

Figure 4. Schematic figure of a rebuild pre-treatment plant with an additional flotation tank (adapted from ("Scandic Pelagic - samrådsunderlag," 2020).

The proposed strategies for disposal of treated process water for alternative 1

Description of a second additional flotation tank have been presented in previous section. For this part, a description of the proposed strategies for disposal of treated process water from S.P to the recipient will be presented. Two different approaches have been recommended for disposal of treated industrial process water in order to implement alternative 1 as solution. These can be presented as alternative 1a and alternative 1b.

Alternative 1a: An additional flotation tank in combination with mussel farms

- By using pipelines from S.P to mussel farms.

This approach implies that the treated industrial process water, using an additional flotation tank, will be transported to the recipient through pipelines from S.P. This means that the mussel farms eventually will compensate the emitted outflow by nitrogen and phosphorous reduction.

Alternative 1b: An additional flotation tank in combination with mussel farms

- By boats, using buffer tanks for transportation of treated process water to mussel farms.

This approach will also include a second flotation tank, but the outflow will instead be directly led to buffer tanks. Meaning that treated process water will be returned to the recipient by pumping the outflow to the vessels' RSW tanks and primary production stimulated by the nutrient-rich water will eventually be used as feed by farmed mussels.

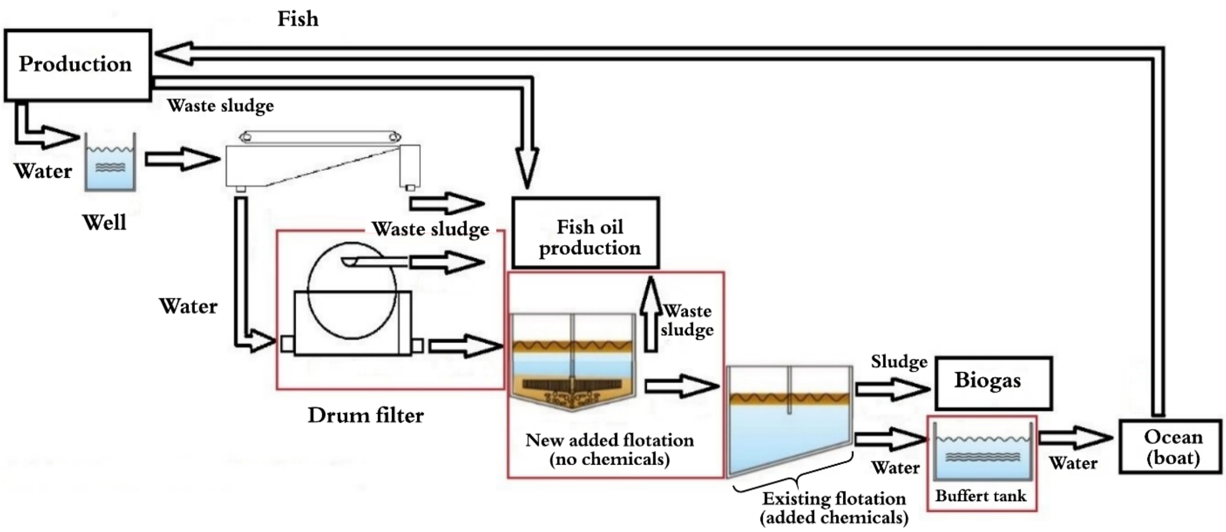

Figure 5. Schematic figure of alternative 1b, using buffer tanks (adapted from ("Scandic Pelagic - samrådsunderlag," 2020).

The entire process from the production phase to the recipient for alternative 1a and 1b is presented in figures 6 and 7. Figure 7 also gives a description of the two suggested ways for transporting treated process water to the recipient and the nutrient cycle of organic material from land to the ocean. The light-yellow boxes are currently existing steps, and the green boxes are representing the new added steps.

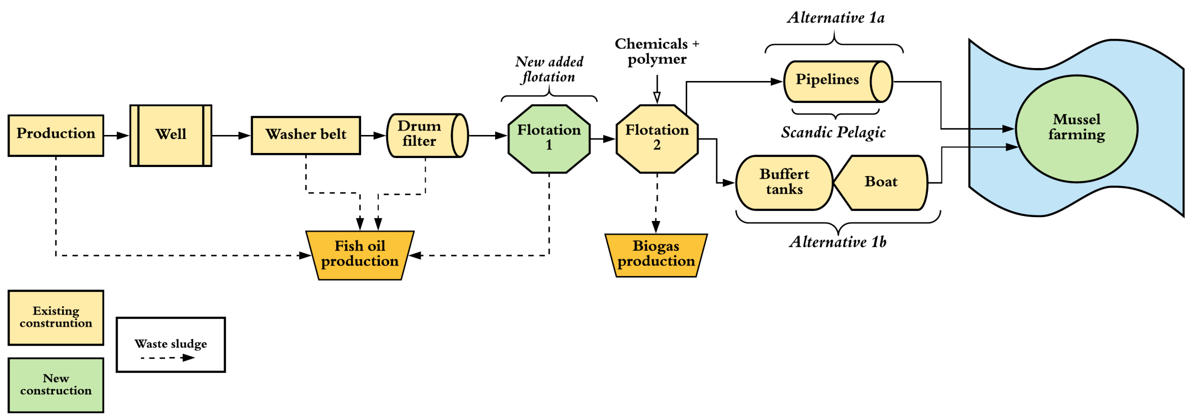

Figure 6. Flowchart for alternative 1a and 1b: Disposal of treated industrial process water from S.P to mussel farms (adapted from ("Scandic Pelagic - samrådsunderlag," 2020).

Figure 7 is presenting similar steps as for figure 5 and 6 but shows a detailed description of how different marine species absorb organic compounds, in other words, how BOD_7, nitrogen and phosphorus naturally can be reduced by water living organisms and the existing food chain as well ("Scandic Pelagic - samrådsunderlag," 2020).

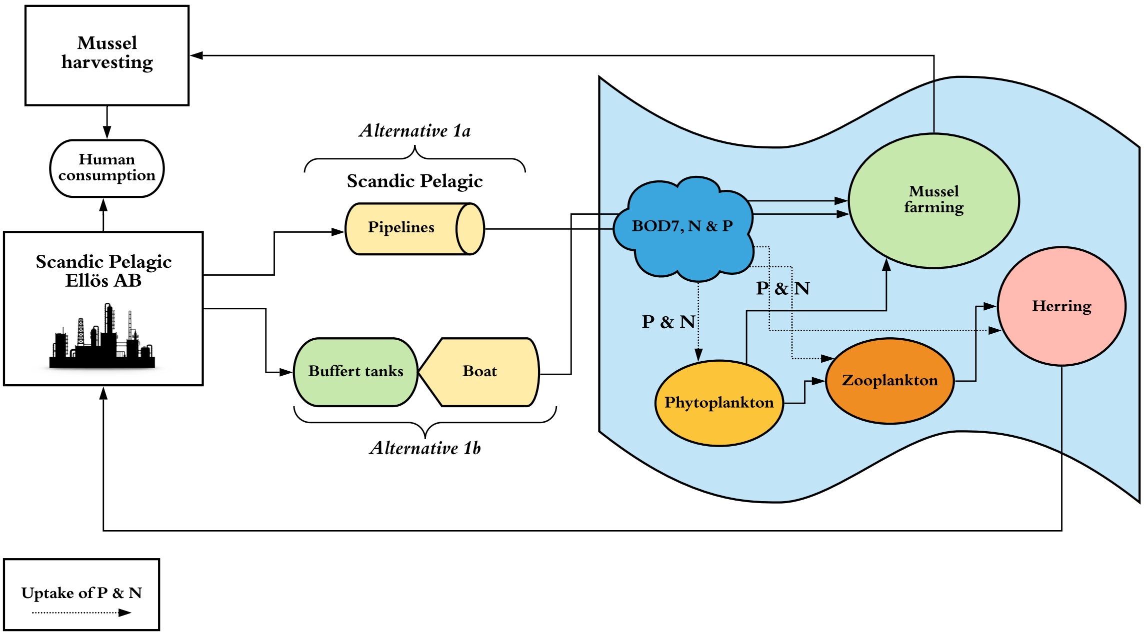

Figure 7. Flowchart for alternative 1a and alternative 1b (adapted from ("Scandic Pelagic - samrådsunderlag," 2020).

Description of mussel farming

Mussel farming is one of the proposed alternatives for further treatment of process water from S.P. The plan is to cultivate a specific number of mussels in order to regain the nutrition and at the same time produce valuable, healthy and environmentally friendly food. Since harvest mussels eventually be used for human consumption while growing new ones.

The idea of using mussel farms as an alternative to remove nitrogen in process water instead of a conventional nitrogen treatment plant operating on land is viewed differently by different stakeholders. According to Naturskyddföreningen, mussel farms cannot replace the conventional treatment plant since the removal of organic compounds must take place at the emission source and not at the recipient. However, mussel farms can be used as an additional treatment of already treated process water, but not as the main WWTP (Nyström, 2006). This in turn, has made it difficult to receive a permission and was confirmed during the consultation meeting with the county administrative board (2020-02-07).

Hence, positive and negatives effects must be considered. The following section will mainly discuss the biological treatment mechanism, strength and weaknesses and several real cases in Sweden of mussel farming as well.

The biological treatment mechanism of blue mussels

The cultivation of mussel farms does not only provide humans with food but are also able to purify the oceans from eutrophying substances. Blue mussels *(Mytilus edulis)* can be referred as filtrating marine species, due to their unique ability to purify water on a natural way. The treatment technique can therefore be seen as a possibly method to prevent eutrophication (Lindahl and Kollberg, 2008). Blue mussels can improve water quality by obtaining oxygen and feeding on filtrating phytoplankton, bacteria, detritus and other suspended material available in seawater, and by that convert nutrients (nitrogen and phosphorous) into mussel meat. The accumulation of nutrients from feed to blue mussel's biomass and the mussel harvesting will result into a net removal of organic compounds from the ecosystem (Svenskt vattenbruk, 2020).

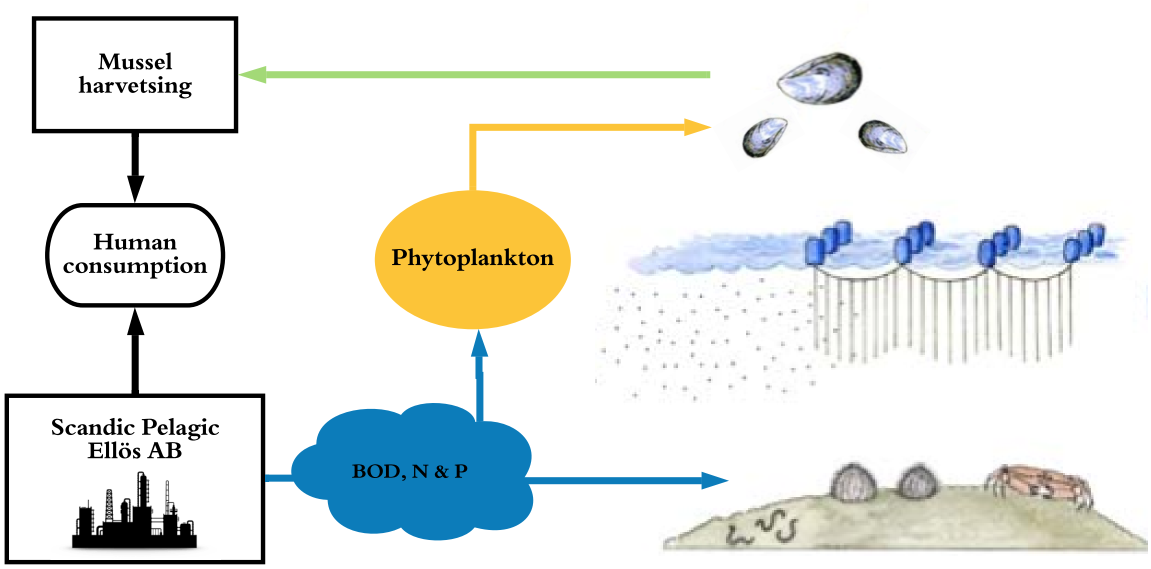

Figure 8. The principle of recycling organic nutrients using mussel farming (adapted from ("Scandic Pelagic - samrådsunderlag," 2020) (Göteborgs universitet, 2014) (Lindahl and Kollberg, 2008))

Because the seawater is constantly moving, mussels constantly gets new organisms to filter even though they are stuck, still able to purify themselves from harmful substances in the same time. The filtrating capacity of mussels tend to vary a lot, depending on size, shape and gill surface area. In general, blue mussels are able to filtrate water at a rate between 1-liter per day and 1-2 liters per hour (Williams, 2020) (Lindahl and Kollberg, 2008) At extremely good conditions, a size of a blue mussel approximately 5cm is able to filtrate up to 5 liters of water per hour (Odd Lindahl, 2005). Meaning that one ton of mussels, in the long run, are able to reduce about 8kg nitrogen and 0.5kg phosphorous from the sea before its time for harvesting, which is usually after 18 months (refers to mussel farms on the Swedish's west coast) (Rosland *et al.*, 2011) (Díaz, Figueroa and Sobenes, 2014).

Method to cultivate blue mussels: Long-line mussel farming

There are multiple ways of cultivating blue mussels, but the most common way in Sweden is by long-line mussel farming. This approach has been developed in Sweden since the early 1980's. Long-line mussel farming uses suspenders roughly about 6m, as these are attached to several horizontal lines at the sea surface, resulting into a series of vertically orientated loops where blue mussels are grown. The long-line technique occupies roughly about 2000m^2 of surface area in a dept of 6m (see figure 9) (Lindahl and Kollberg, 2008) (Svenskt vattenbruk, 2020).

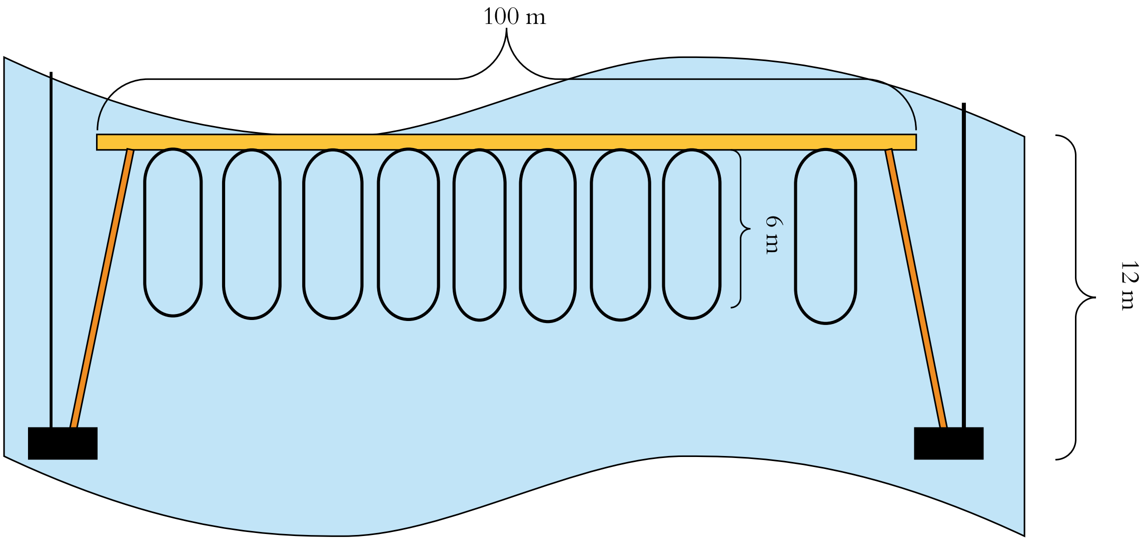

Figure 9. Schematic principle of long-ling mussel farming (adapted from (Hedberg *et al.*, 2018)).

Limitations

Multiple factors must take into account for evaluating the performance of mussel farms. Depending on the location, the set-up (size and density of blue mussels) and water conditions, (salinity and pH-level) and nutrient availability will highly effect blue mussel's nutrient uptake capacity and the nutrient cycling in general. For instance, a low salinity level affects the osmotic ratio in the water, meaning that mussels are forced to allocate a majority of its energy for osmoregulation. Blue mussels are thereby put under high physiological stress, resulting into less energy available for growth and nutrient uptake (Hedberg *et al.*, 2018)

However, mussel farms tend to grow better on the West coast due to better aquatic environment e.g. better salt content, compared to the Baltic Sea (Hedberg *et al.*, 2018). In Västra Götaland, the investment in mussel farms has increased over the years. As a result, the county government of Västra Götaland could present a positive result in the action program against eutrophication of a reduction of approximately 2750 tonnes nitrogen annually since 2011 for coastal water (Odd Lindahl, 2005). A permission from (in this case) the county government in Gothenburg must be approved for cultivating blue mussels and the application must be assessed according to the Swedish Environmental Code and Fiskeriförordningen (1994:1716) (Länstyrelsen, 2014).

Possible locations and size of mussel farming

An important factor to keep in mind for this case is that the mussel farms can not be cultivated around near areas of the treatment plant of the municipality's emissions point. In order to prevent mussels from getting contaminated by e.g. pathogenic microorganisms, medical residues or other possible pollutants. However, the locations are still not yet identified, this is still an on-going process.

In order to achieve a sufficient nitrogen reduction of the industrial process water, an estimation of approximately 819ton blue mussels is required annually. The total amount of mussels is correlated to the total amount of nitrogen (9098kg) emitted from S.P to the recipient annually. It is further assumed that the harvest may vary every year depending on the size, supply of mussels feed, weather condition etc. Although, mussels are usually harvest after 1.5 years with an estimated size about >5cm (Lindahl, 2020) ("Scandic Pelagic - samrådsunderlag," 2020).

The environmental impacts and risks of cultivating mussels

Blue mussels' unique ability to live on filtrating plankton other nutrients available in the ocean and thereby recycling nutrients from sea to land, can for many be recognized as an environmental tool against eutrophication. Mussel farming has been proven by several studies to have significant lower environmental impact, compared to other similar approaches, such as fish farming (Kautsky and Evans, 1987). Indeed, cultivating blue mussels can have several positive impacts on the marine environment, at the same time, may also have negative effects.

A case study from Sweden 1987, could present the local environmental effects of mussel farming in the Baltic Sea. Based on the report, the phytoplankton did only contain in average 25% (range 5-45%) of nutrients while the blue mussels consumed these. The remaining (75%) of nutrients were instead excreted to the ocean as dissolved nutrients or during spawning period turned into eggs and sperms and converted into mussel feces and pseudofeces, resulting that the biodepositions gradually creates a sediment build up at the seabed. Furthermore, may inhibit vegetations below the cultivated farms to grow and have negative effects on the oxygen and nutrient cycle as well (Hedberg *et al.*, 2018) (Schröder *et al.*, 2014).

From the start, mussel farms have also been recognized as a tool for improving water clarity. However, this can not be assured for every case. An investigation of a relatively small mussel farm (30ton ww mussels harvested annually) effect on water clarity was studied in Kiel Fjord, Germany 2014. Schröder could present how only 30cm in Secchi dept within the cultivated area and only about 5 cm around the mussel farm was improved (Lorenzen, 1980; Bayne, 2009)(Petersen *et al.*, 2008). A reasonable argument for this issue is to solve this by increasing the density of mussel farms, because a larger farm would generate into greater improvements of water clarity. Though, this is a far complex treatment mechanism than expected. In his work, Lorenzen could conclude that increasing the number of mussels, the water clarity would only be improved by a marginal difference. According to Lorenzen, there's an inverse logarithmic correlation between the density of phytoplankton and the Secchi depth. Furthermore, blue mussel's particle removal efficiency is decreasing logarithmically with the concentration of particle. Meaning that these conditions explains why an improvement of doubling Secchi depth, for example 30cm to 60cm, can not easily be solved by doubling the density or size of the mussel farms. This will instead require a significantly larger increasement that expected (Cermeño *et al.*, 2006)

Another study in 2004, Ría de Vigo, Spain, could show the effects mussel farming had on the concentration of phytoplankton. The study could present and observe how a large scale of mussel farms lead to clear depletion of phytoplankton in certain areas around the cultivation unit. As mentioned in previous section, phytoplankton is the primary food source and the driving force for the treatment mechanism of mussels. If these can not be fed frequently, mussel farms can due to food depletion be quite limited. Generating into smaller size, harvests and thereby significantly less nutrient removed from the oceans (Frösell and Karlsson, 2019).

In Sweden 2019, an LCA report was conducted for assessing the environmental impacts regarding mussel cultivation for food production. The studied mussel farm was located in Göteborg, Orust. For this case, the two selected impact categories were global warming potential (CO_2-eq) and eutrophication potential (kg PO4-eq). The production size of this farm was approximately 5000 ton per year, but different scenarios were studied. When studying the side effects (improved water quality) of the mussel farm, a correlation between nutrient uptake and mussel size could been observed. The different scenarios were assessed on how the nutrient uptake was correlated to the size of blue mussels and the environmental impact. The findings in the report confirmed that the nutrient uptake was significant higher for bigger mussels compared to smaller ones. The biggest contributor to CO_2-emissions were replacing worn out materials and fuel consumption within maintenance and harvesting activities (Wang *et al.*, 2019).

Applications

In order to maximize the utilization of mussel farming, S.P has decided that harvested mussels will be used for human consumption. Besides for human consumption, blue mussels are also commonly used in agriculture, such as animal feed. As this alternative is a good way for utilizing broken or too small mussels, thereby generating into less waste (De Blois and Engström, 2019).

3.2.2 Alternative 2: An additional flotation tank + MBBR technology + sedimentation, using pipelines for disposal to ocean.

Description of the new wastewater treatment plant: The MBBR technology

The MBBR technology consist of a cylindrical batch (700m^3) and shall be operated after the pre-treatment plant. This approach uses biocarriers in order to cultivate biofilms for removal of organic matter from the process water influent. In addition, stirrer and air-blower system will be applied during treatment for a more efficient system. In order to prevent excessive load in the MBBR, an additional batch will be placed after the MBBR and the influent will instead be treated with chemicals, but only when the MBBR is over-loaded. For the final step, separation of sludge and treated water will then take place in a sedimentation tank and excess sludge will either be reused for the MBBR or for digestion. The remaining effluent are then transported to the recipient through the pipelines from S.P (see figure 10). As seen in figure (10), several essential construction components can be purchased as used construction components (de Blois and Engström, 2019)

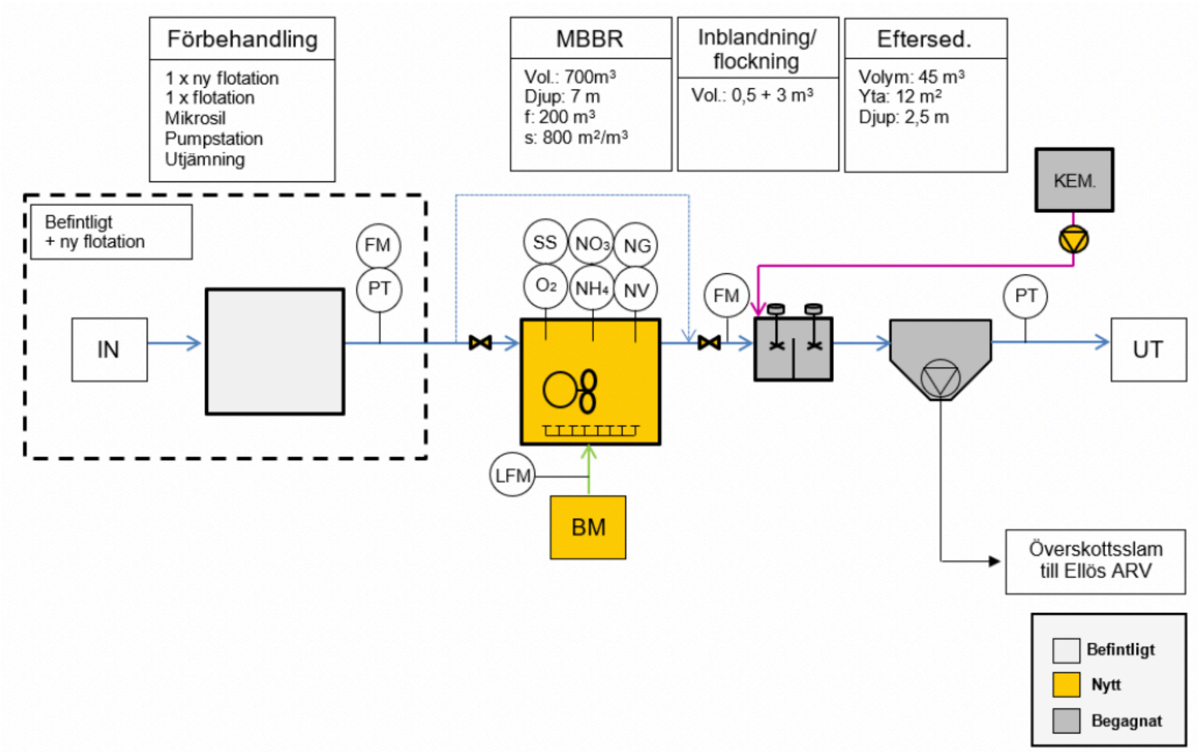

Figure 10. Schematic figure of alternative 2, using the MBBR technology (De Blois and Engström, 2019)

The performance of MBBR

The Moving bed biofilm reactor (MBBR) technique, as for the SBR technique, is also a common treatment method for wastewater and was developed in the 1980's. The reactor can both be used during anaerobic or aerobic conditions where a large amount of free-moving plastic biocarries are placed into the pool for the growth of biofilms. The use of biofilms makes it easier to monitor and control the reactions and growth rate of microorganisms. Nutrients available in wastewater are used as feed supply for microorganisms and the removal of pollutant from wastewater enables the biological treatment process. Organic compounds are thereby reduced from the influent wastewater as the biofilms absorbs the amount of nutrients. In general, the biofilms' life cycle phase involves three major steps; formation (incl attachment), growth and detachment. In order to achieve a more efficient system, energy must be applied for an even distribution throughout the process. This is often solved by applying some form of mechanical performance e.g. mixing or aeration (Wang *et al.*, 2019).

The plastic biocarriers are usually filled up to 50% of the total volume of the MBBR before start-up and are held in place by silage cages which will prevent them from following the treated water out of the basin. The characteristics of the biofilm carrier may vary in size, shape, dimension and usually made of polyethylene. The characteristics are highly important because of its effects on the performance of the MBBR (de Blois and Engström, 2019) (Wang *et al.*, 2019)

Advantages and disadvantages for the MBBR technology

The MBBR technique has been proven to be very effective treatment method from an environmental point of view but costly. Still, this approach may imply several operational issues such as, blocking of pipelines, nonhomogeneous mixing, broken biocarriers or accumulation of carriers for instance. The free-moving plastic carriers may also block the silage cages meaning that the construction can be quite sensitive for high fat and fiber content. Another disadvantage is that the produced sludge has poorer sedimentation properties than the conventional active sludge. However, many of these issues can be solved by better design, equipment or overall operation construction (Nylöf, 2018).

3.2.3 Alternative 3: An additional flotation tank + SBR technology, using pipelines for disposal to recipient.

Description of the new wastewater treatment plant: The sequencing batch reactor (SBR)

For this alternative, S.P shall build a treatment reactor tank, operated as a batch and shall be placed after the current pre-treatment process (see figure 11). This approach implies that the reactor will be filled half of the total volume (1400m^3) with an active biological sludge (~700m^3). During operation, the industrial process water (~700m^3) and the sludge is stirred together by using supplied aeration. The stirring is applied for achieving anaerobe conditions and denitrification occurs. While the aeration is applied for achieving aerobe conditions and nitrification occurs. The biological treatment mechanism occurs as the microorganisms in the sludge break down and reduce the amount of organic matter in the incoming process water. Sedimentation of the biological sludge can then take place in the same reactor, approximately during 1-2h. As a result, the sludge drops to the bottom of the reactor and a clear water phase appears in the top of the reactor. The treated water is then separated by decantation and then emitted to the recipient. Excess sludge from sedimentation is transported to the sludge treatment plant of the municipality (De blois and Gunnarsson, 2020).

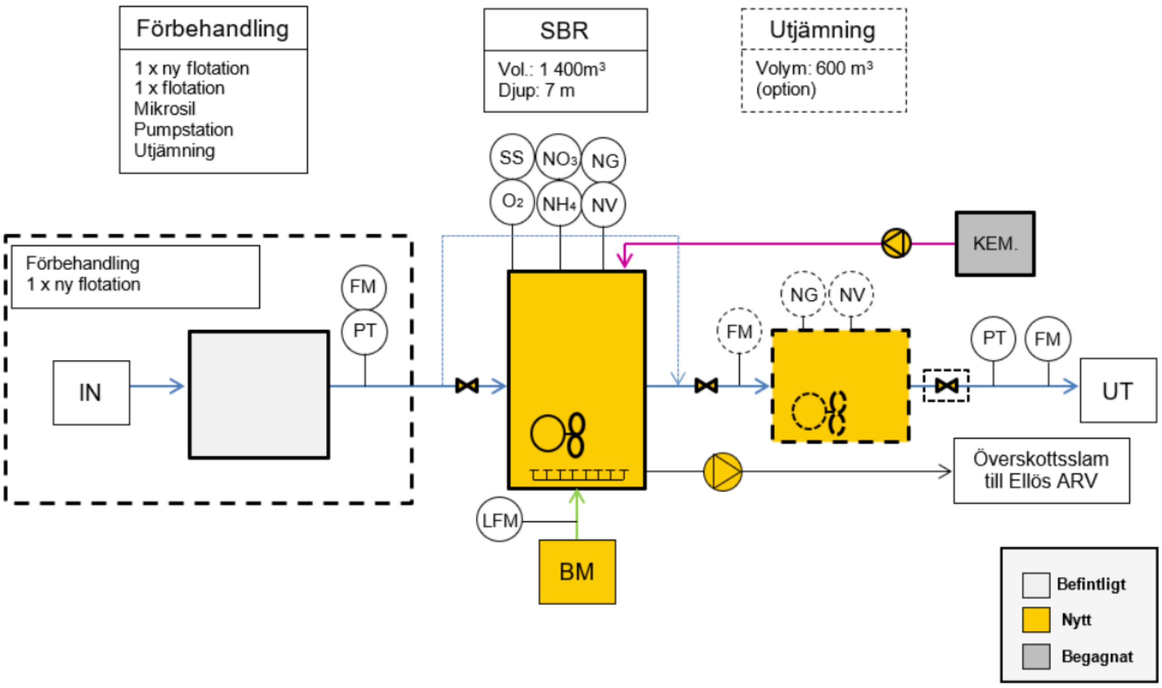

Figure 11. Schematic figure of alternative 2, using the SBR technology (adapted from (De Blois and Gunnarsson, 2020)).

The performance of SBR

The sequencing batch reactor (SBR) is a common method for treatment of wastewater due to its natural mechanism to purify water. As seen in figure 12, the biological mechanism uses active sludge, which is mixed with wastewater in a batch while microorganisms are feeding on available nutrients, generating into a reduction of the organic compounds. The SBR, is both operated during aerobic and anaerobic conditions mainly to achieve an efficient denitrification, nitrification and phosphorus reduction. By sedimentation, the sludge is then settled at the bottom of the reactor and separated from the effluent by decantation (Gao, He and Wang, 2019; Liu *et al.*, 2020).

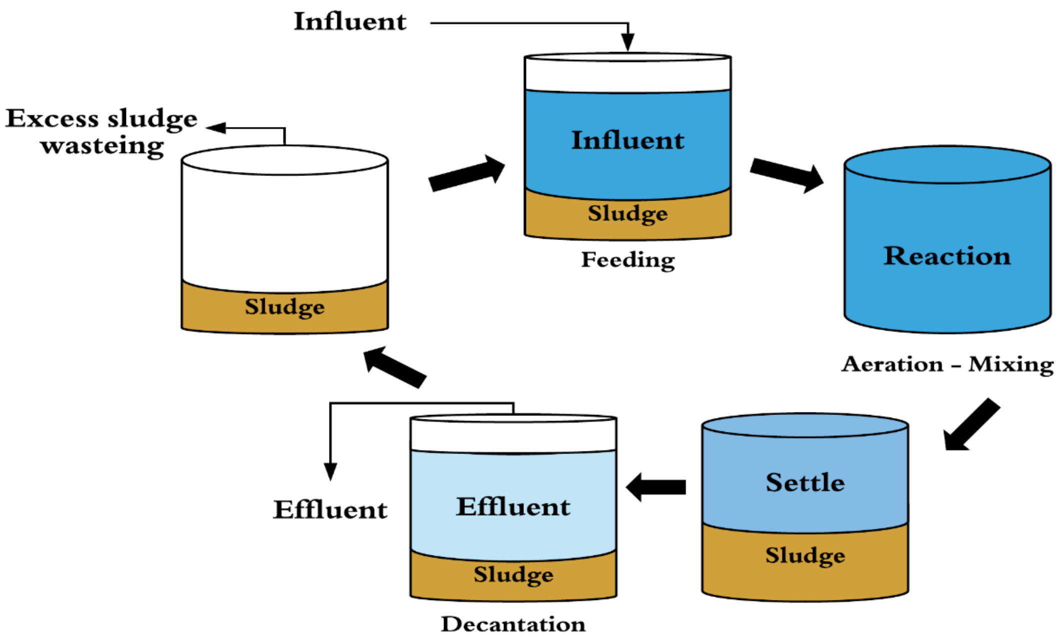

Figure 12. The general process of sequencing batch reactor (SBR) technique (adapted from (Gao, He and Wang, 2019)).

Advantages and disadvantages for the SBR technology

The main advantages for SBR are its unique ability to achieve a high nutrient reduction, including high operational flexibility and stability with a simple structure. As mentioned, the sedimentation process take place in the same reactor, generating into lower operating costs and minimal footprint, compared to similar technologies (EPA, 1999).

However, the SBR often require a higher level of sophistication and maintenance than conventional systems. At the same time, the risk of potentially discharging settled sludge during operation and plugging of aeration devises are relatively high (Naturvårdsverket, 2012).

3.3 Delimitations

All proposed alternatives for S.P (see table 1) were not included for evaluation in this report, only the presented alternatives in table 3.

This work did not assess or evaluate any economic aspects regarding S.Ps' current wastewater treatment plant and the proposed alternatives.

Data, regarding material construction of Ellös ARV and boat (Stella Nova) for transportation were not included. However, data of required energy use from Ellös ARV and the boat was included in the analysis. This is mainly due to the high uncertainties regarding the design construction of these.

3.4 Description of life cycle assessment (LCA)

For this work, life cycle assessment (LCA) was chosen as a tool in order to evaluate and assess the environmental impacts of the alternative treatment plans.

The functional unit (FU) for this assessment is **kg N removed through the treatment, corresponding to 5600 liter of treated process water**. Since the goal and purpose with wastewater treatment plants is to reduce available nutrients and improve the effluent quality.

The LCA is evaluating the input data based on the functional unit into certain **impact categories**, the selected categories for this work are **global warming (kg CO_2-eq)** and **eutrophication (kg N-eq)**. These impact categories were selected due to their association with wastewater treatment.

The **system boundaries** were set to cover the production of raw materials needed for infrastructure construction as well as energy and chemical consumption during operation.

Allocation was dealt with based on product mass. Mass allocation was chosen over economic allocation since allocation based on physical relationships is recommended over other methods such as e.g. economic allocation in the ISO14040 standard.

3.5 General assumptions

In order to establish an LCA analysis based on the provided data, some general assumptions had to be made. The list below presents all assumptions that were made for this work and will be taken into account for all options.

List of the general assumptions for this work

- S.P did confirm that the boat Stella Nova, could be used in alternative 1b - Pre-treatment plant + mussel farm (boat) for transporting process water from S.P to mussel farm. Hence, the inventory data was based on the requirements of Stella Nova.

- Data of construction materials for Ellös ARV and the material use for the boat (Stella Nova) for transporting treated process water from S.P to the recipient was not included in the LCA analysis of the proposed alternatives. However, the amount of energy and chemicals required from these were included in the assessment.

- Hence, the inventory data of alternative 0 - S.Ps' current WWTP includes chemical and energy consumption used in the pre-treatment plant and Ellös ARV. However, the required material consumption used in the pre-treatment plant is included but not Ellös ARV. Inventory data of material consumption for the boat (Stella Nova) used in alternative 1b - Mussel farm (boat) is excluded in this work.

- The total amount of annual produced industrial process water and nitrogen emissions from S.P used for the calculations was a mean amount based on the years 2017-2019. The total weight of the materials was set at a level based on the largest share of production material.

- All LCA data regarding mussel farms is based on the master thesis Runesson (2020) and is included for the result of this work. The given LCA values are mean values from different LCA studies of mussel farms.

- The chemical use of Duramax-b1022 (ceramic binder, an aqueous emulsion for enhancing strength of industrial ceramic parts), used for all assessed alternatives were not included for this work due to lack of data.

Regarding the required materials used for the alternative treatments, lifespan of construction components, type of material and total weight of the materials was based on estimations by S.P, meaning that the provided data used in this work is subject to some uncertainty.

- The total weight of the materials was set at a level based on the largest share of production material.

- The type of material for the construction components was also chosen by the largest share of production material

- The lifespan of the construction components was set based on their economic value. Here, the lifespan ends when the economic value of the component is zero.

3.6 Life cycle inventory (LCI)

This section will describe how data was collected for this work, data sources and how the these were used for the calculations.

Data regarding material, construction, energy resources, wastewater content, reduction efficiency and emissions levels for the alternatives was mainly provided from Scandic Pelagic AB and H2OLand AB. LCA data of mussel farms was provided from Runesson (2020) and is taken into account together with the result provided from this report. Further data for production of supply materials and energy from the LCA database ecoinvent (v3) was used for all calculations. In order to evaluate the environmental impacts of the removal of 1kg nitrogen in process water, data of chemical, material and energy requirements for each assessed alternative were converted into values based on the functional unit. Data from ecoinvent (v3) in SimaPro could then provide the environmental impact of the required chemical, energy and material use in order to reduce 1 kg nitrogen.

4 Results

This chapter will present the results of this work, based on the purpose of the research (see chapter 2) and is mainly divided into three sections. The first section will present the result of the removal efficiency levels of organic matter and nutrients for all assessed alternatives and a comparison to the average removal efficiency levels of organic matter from WWTPs in Sweden. The second part of this chapter will present the environmental impact of the assessed alternatives based on the impact categories and the functional unit of this LCA study. The third section will present a short summary of all proposed alternatives, including the excluded ones, providing with a general evaluation from an environmental and economic point of view. A deeper discussion and analysis based on the results will be presented in chapter 5.

4.1 The removal efficiency levels of organic matter

Tables 3-8 show the removal efficiency levels of BOD, nitrogen and phosphorus for the assessed options. In addition, the average removal efficiency levels of organic matter for WWTPs in Sweden is also presented in order to show a comparison of the assessed nutrient removal efficiency levels with existing average values (also presented in chapter 1.2). A more detailed result and the comparison can be observed in tables 4-8. The presented data of the removal efficiency levels of organic matter and nutrients in table 3-8 were provided from S.P and Naturvårdsverket (Naturvårdsverket, 2012a).

Based on the results observed in table 3-8, alternative 0 - S.Ps' current WWTP, alternative 2 - MBBR, alternative 3 - SBR and alternative 3* - SBR (+surge tank) have the highest reduction level of BOD with similar levels at a range of 90-95%, which also reflects the average value of 95%. When studying alternative 1a - Pre-treatment plant + mussel farm (pipelines) and 1b - Mussel farm (boat), only 30-60% of BOD can be removed and therefore generating a greater difference from the average value.

However, alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat) have the highest nitrogen reduction level by 100%, followed by alternative 2 and 3 at ~80% and currently above the average value at 60-70%. Alternative 0 -S.Ps' current WWTP is only able to reduce 25% of nitrogen, resulting to a significant higher difference compared to the other options. The low removal efficiency level of nitrogen is due to the yet none existing nitrogen purification requirement in this alternative (confirmed by S.P). Hence, mainly BOD and phosphorus are reduced in this process.

For the removal efficiency level of phosphorus, alternative 2 and 3 are able to remove approximately 90-95% of phosphorus and once again at very similar levels to the average value at 90-95%. Alternative 0 - S.P current WWTP is instead able to remove 85% and only a small difference can be observed compared to the average value. Though, alternative 1a and 1b have a removal efficiency level of 60-100% and in this case have the highest but also the smallest difference from the average value.

Table 3. The removal efficiency level of organic compounds; BOD, nitrogen and phosphorus for the given options and WWTPs (average) in Sweden.

All options	**Removal efficiency level (%)**		
	BOD	**Nitrogen**	**Phosphorus**
0) S.Ps' current WWTP	92	25	85
1a) An additional flotation tank, using pipelines for disposal to mussel farms.	30-60	100	60-100
1b) An additional flotation tank, using boats for disposal to mussel farms.	30-60	100	60-100
2) An additional flotation tank + MBBR technology + sedimentation, using pipelines for disposal to the recipient.	90-95	~ 80	90-95
3) An additional flotation tank + SBR technology, using pipelines for disposal to recipient.	90-95	~ 80	90-95
3*) An additional flotation tank + SBR technology + surge tank, using pipelines for disposal to recipient.	90-95	~ 80	90-95
• **Average WWTPs in Sweden**	95	60-70	90-95

Table 4-8 presents the removal efficiency levels of all assessed alternatives and a comparison to the existing average removal efficiency levels for WWTPs in Sweden. Red values indicate that the assessed alternative is not meeting the average value of the specific organic compound or nutrient. Green values indicate that the assessed alternative is meeting the average value. While yellow values are partly meeting the average values.

Table 4. A comparison of the removal efficiency level of organic compounds for S.Ps' current WWTP and WWTPs (average) in Sweden.

	Removal efficiency level (%)	**Difference (%)**
BOD		
Alternative 0	92	3
Average WWTPs in Sweden	95	
Nitrogen		
Alternative 0	25	35-45
Average WWTPs in Sweden	60-70	
Phosphorus		
Alternative 0	85	5-10
Average WWTPs in Sweden	90-95	

Table 5. A comparison of the removal efficiency level of organic compounds for alternative 1a - Pre-treatment plant + mussel farm (pipelines) and WWTPs (average) in Sweden.

	Removal efficiency level (%)	**Difference (%)**
BOD		
Alternative 1a	30-60	35-65
Average WWTPs in Sweden	95	
Nitrogen		
Alternative 1a	100	+(30-40)
Average WWTPs in Sweden	60-70	
Phosphorus		

Alternative 1a	60-100	5-35
Average WWTPs in Sweden	90-95	

Table 6. A comparison of the removal efficiency level of organic compounds for alternative 1b - Pre-treatment plant + mussel farm (boat) and WWTPs (average) in Sweden.

	Removal efficiency level (%)	**Difference (%)**
BOD		
Alternative 1b	30-60	35-65
Average WWTPs in Sweden	95	
Nitrogen		
Alternative 1b	100	+(30-40)
Average WWTPs in Sweden	60-70	
Phosphorus		
Alternative 1b	60-100	5-35
Average WWTPs in Sweden	90-95	

Table 7. A comparison of the removal efficiency level of organic compounds for alternative 2 -MBBR and WWTPs (average) in Sweden.

	Removal efficiency level (%)	**Difference (%)**
BOD		
Alternative 2	90-95	0-5
Average WWTPs in Sweden	95	
Nitrogen		
Alternative 2	80	+10-20
Average WWTPs in Sweden	60-70	
Phosphorus		
Alternative 2	90-95	0
Average WWTPs in Sweden	90-95	

Table 8. A comparison of the removal efficiency level of organic compounds for alternative 3 and 3* - SBR (+surge tank) and WWTPs (average) in Sweden.

	Removal efficiency level (%)	**Difference (%)**
BOD		
Alternative 3 and 3*	90-95	0-5
Average WWTPs in Sweden	95	
Nitrogen		
Alternative 3 and 3*	80	+10-20
Average WWTPs in Sweden	60-70	
Phosphorus		
Alternative 3 and 3*	90-95	0
Average WWTPs in Sweden	90-95	

4.2 The inventory data of the assessed alternatives

Figure 13-18 presents the inventory data for the assessed alternatives (type of materials, chemical and energy) and the results of the impact categories; global warming and eutrophication based on the functional unit (kg N removed through the treatment, corresponding to 5600liter of treated process water). A more detailed description of the inventory data and calculations for this work are also presented in chapter 9, appendix (A.1-5).

When analyzing figures 13-18 and comparing the material use for all alternatives, the greatest material consumption can be observed for alternative 1a - Pre-treatment plant + mussel farm (pipelines) lowest material consumption can be observed for alternative 0 - S.Ps' WWTP. When comparing the chemical use for all alternatives, the greatest chemical consumption can be observed for alternative 2 - MBBR and lowest chemical consumption can be observed for alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat). The highest energy consumption can be observed in alternative 1b - Pre-treatment plant + mussel farm (boat) and lowest in alternative 0 - S.Ps' current WWTP. A further proposal for alternative 3 - SBR was to implement a surge tank, hence alternative 3* - SBR (+surge tank).

Alternative 0: S.Ps' current WWTP			
Chemical use	**Value**	**Global warming (kg CO2-eq)**	**Eutrophication (kg N-eq)**
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.14	1.66*10^-4
Polyaluminiumchloride (PAX)	12.79 kg	68.12	1.74*10^-3
Polyacrylamides	0.048 kg	0.13	1.02*10^-4
Energy use			
Electricity, Swedish grid	102.1 MJ	2.960	1.21*10^-4
Material use			
Polyethylene (HDPE)	0.0043 kg	0.0092	1.28*10^-8
Injection moulding	0,0043 kg	0.0058	2.06*10^-7
Stainless steel	0.018 kg	0.037	9.64*10^-7
	Total value	**74.63**	**2.44*10^-3**

Figure 13. The inventory data of alternative 0: S.Ps' current WWTP and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

Alternative 1a: Pre-treatment plant + mussel farm (pipelines)			
Chemical use	**Value**	**Global warming (kg CO2-eq)**	**Eutrophication (kg N-eq)**
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.13	1.66*10^-4
Polyaluminiumchloride (PAX)	9.29 kg	49.5	1.26*10^-3
Energy use			
Electricity, Swedish grid (WWTP)	20.82 MJ	0.6034	5.57*10^-4
Electricity and fuel consumption (Mussel farm)		23.93	1.28*10^-8
Material use			
Polyethylene (HDPE)	0.102 kg	0.220	3.04*10^-7
Injection moulding	0.102 kg	0.320	4.89*10^-6
Stainless steel	0.025 kg	0.054	1.34*10^-6
Mussel farm: Long line		45.48	2.90*10^-3
	Total value	**123.46**	5.26*10^-3

Figure 14. The inventory data of alternative 1a: Pre-treatment plant + mussel farm (pipelines) and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

Alternative 1b: Pre-treatment plant + mussel farm (boat)			
Chemical use	**Value**	**Global warming (kg CO2-eq)**	**Eutrophication (kg N-eq)**
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.13	1.66*10^-4
Polyaluminiumchloride (PAX)	9.29 kg	49.5	1.26*10^-3
Energy use			
Electricity, Swedish grid	18.50 MJ	0.5365	5.54*10^-4
Electricity and fuel consumption (Mussel farm)		23.93	3.54*10^-4
Diesel fuel production (Boat)	2.52 kg	1.33	2.17*10^-5
Diesel fuel combustion (Boat)	2.52 kg	8.05	7.96*10^-3
Material use			
Polyethylene (HDPE)	0.0043 kg	0.0093	1.28*10^-8
Injection moulding	0.0043 kg	0.21	2.06*10^-7
Stainless steel	0.025 kg	0.053	1.34*10^-6
Mussel farm: Long line		45.48	2.90*10^-3
	Total value	**132.47**	**1.32*10^-2**

Figure 15. The inventory data of alternative 1b: Pre-treatment plant + Mussel farm (boat) and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

Alternative 2: MBBR			
Chemical use	Value	Global warming (kg CO2-eq)	Eutrophication (kg N-eq)
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.13	1.66*10^-4
Polyaluminiumchloride (PAX)	14.18 kg	75.52	1.92*10^-3
Energy use			
Electricity, Swedish grid	118.08 MJ	3.4243	1.41*10^-4
Material use			
Steel	0.048 kg	0.10	2.57*10^-6
Stainless steel	0.025 kg	0.054	1.34*10^-7
Concrete	2.94 kg	2.40	1.92*10^-5
Aluminium	0.0009 kg	0.009	3.32*10^-6
Injection moulding	1.69 kg	0.130	8.11*10^-5
Polyethylene (HDPE)	1.69 kg	3.66	5.07*10^-6
	Total value	**88.68**	2.35*10^-3

Figure 16. The inventory data of alternative 2: MBBR and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

ALTERNATIVE 3: SBR			
Chemical use	Value	Global warming (kg CO2-eq)	Eutrophication (kg N-eq)
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.13	1.66*10^-4
Polyaluminiumchloride (PAX)	9.29 kg	49.5	1.26*10^-3
Energy use			
Electricity, Swedish grid	103.05 MJ	3.0015	1.23*10^-4
Material use			
Polyethylene (HDPE)	0.00103 kg	0.00222	3.07*10^-9
Injection moulding	0.00103 kg	0.000550	5.71*10^-7
Steel	0.036 kg	0.0773	1.93*10^-6
Stainless steel	0.025 kg	0.053	1.34*10^-6
Concrete	5.87 kg	4.80	3.83*10^-5
	Total value	**60.78**	**1.6*10^-3**

Figure 17. The inventory data of alternative 3: SBR and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

ALTERNATIVE 3: SBR (+surge tank)			
Material	Value	Global warming (kg CO2-eq)	Eutrophication (kg N-eq)
Sulphuric acid	1.96 kg	0.235	1.02*10^-5
Sodium hydroxide	2.28 kg	3.13	1.66*10^-4
Polyaluminiumklorid (PAX)	9.29 kg	49.5	1.26*10^-3
Energy use			
Electricity, Swedish grid	139.03 MJ	4.0318	1,65E-04
Material use			
Polyethylene (HDPE)	0.00103 kg	0.00222	3.07*10^-9
Injection moulding	0.00103 kg	0.000550	5.71*10^-7
Steel	0.036 kg	0.0773	1.93*10^-6
Stainless steel	0.025 kg	0.053	1.34*10^-6
Concrete	8.99 kg	7.35	5.86*10^-5
	Total value	**64.37**	**1.75*10^-3**

Figure 18. The inventory data of alternative 3*: SBR (+surge tank) and the results of global warming and eutrophication impact for reducing 1kg of nitrogen.

4.3 The environmental impacts of assessed alternatives

The results of the environmental impacts based on the chosen impact categories; global warming (kg CO_2-eq) and eutrophication (kg N-eq) and the functional unit (kg N removed through the treatment, corresponding to 5600liter of treated process water) are further presented in figures 20-21 and tables 9-10. Table 11 presents the degree of highest and lowest emission contributor for all assessed alternatives.

In figure 19, results of the GW impact for alternative 0-3* are presented. The bar charts present the share of energy, material and chemical use of the total GW impact of each alternative. By interpreting figure 20, alternative 1b - Pre-treatment plant + Mussel farm (boat), has the highest

GW impact with 132kg CO_2-eq. While alternative 3 - SBR has the lowest impact with 61kg CO_2-eq. If the additional surge tank was found to be needed, approximately 5.9% higher GW would be contributed. When comparing alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat), the estimated difference by transporting the process water by boat is generating 7.3% more GW impact compared to the use of pipelines.

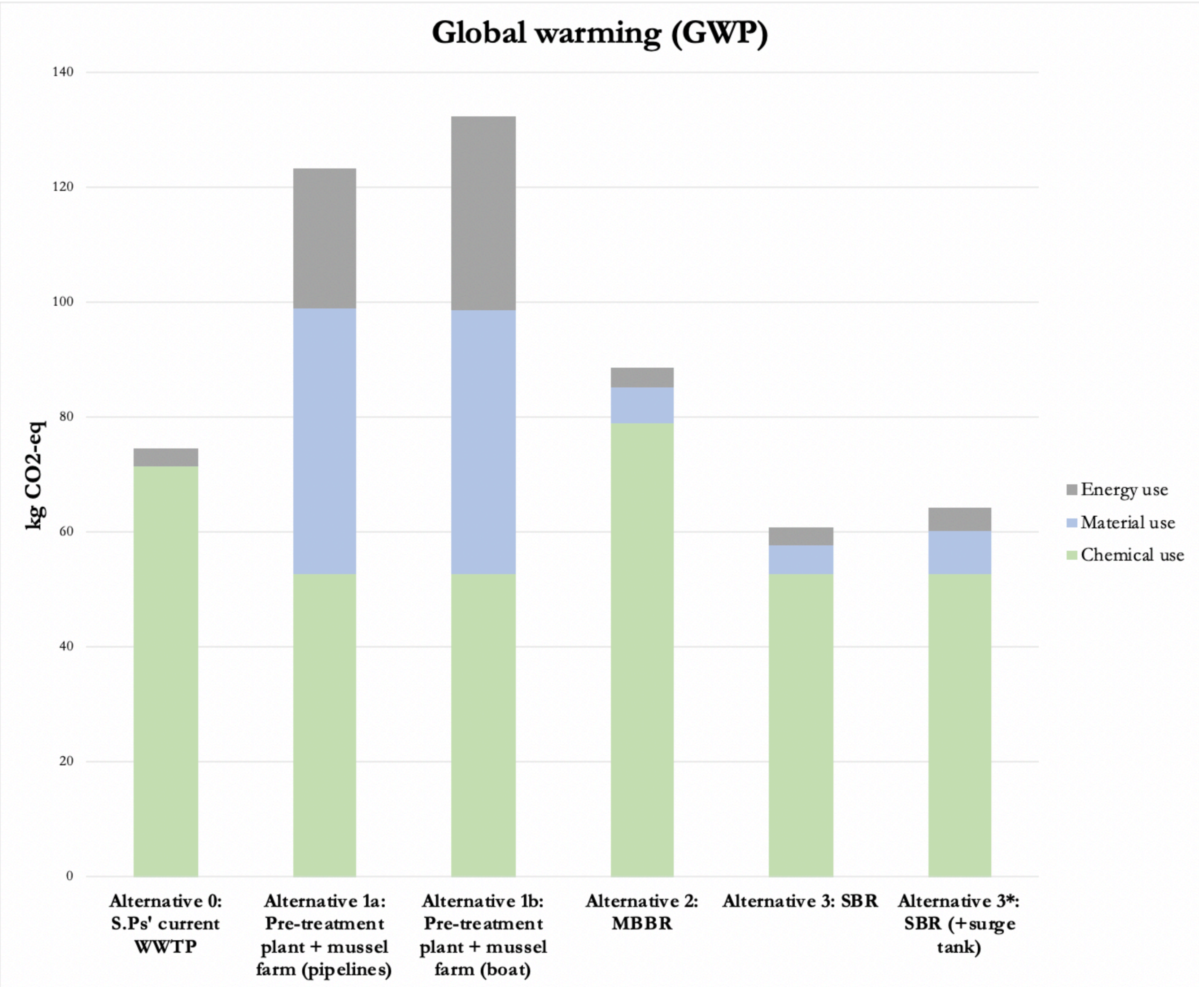

Figure 19. The GW impact of kg N removed through the treatment, corresponding to 5600liter of treated process water for alternatives 0-3* and the share of energy, material and chemical use of total impact.

A more detailed result (in %) of the environmental impacts caused by chemical, energy and material use of the total GW impact for alternatives 0-3* is presented in table 9. Table 9 strongly indicates that the chemical use is contributing most global warming for all assessed alternatives. The second greatest contributor for alternatives 1a-3* is material use, followed by energy use. However, the greatest GW contributor for alternative 0 is indeed chemical use but the second greatest contributor is energy use followed by material use. Yet, alternative 0 - S.Ps' current WWTP has the smallest share of both material and energy use compared to the other assessed alternatives but has the highest share of chemical consumption among all. Since, the largest share of material use is observed in alternative 1a - Pre-treatment plant + mussel farm (pipelines). As further observed, the largest share of energy use can be observed in alternative 1b - Pre-treatment plant + mussel farm (boat).

Table 9. The share of chemical, energy and material consumption for alternatives 0-3* based of GWP.

	Material use (%)	Chemical use (%)	Energy use (%)	GW
Alternative 0	0.1	96	4.0	74.64
Alternative 1a	37	43	20	123.47
Alternative 1b	35	40	25	132.47
Alternative 2	7.2	89	4.0	88.7
Alternative 3	8.1	87	5.0	60.8
Alternative 3*	12	82	6.3	64.4

The results of the eutrophication impact for alternatives 0-3* are presented in figure 20. Figure 20 also presents the share of energy, material and chemical use of the total eutrophication impact of each alternative.

When interpreting the results, alternative 3 - SBR is contributing least eutrophication impact (0.0016kg N-eq), while alternative 1a - Mussel farm (boat) is generating most eutrophication impact (0.013kg N-eq). The relatively high EP value for alternative 1b is mainly due to the required diesel fuel consumption for the boat. Again, this is only the impact results of material, chemical and energy consumption.

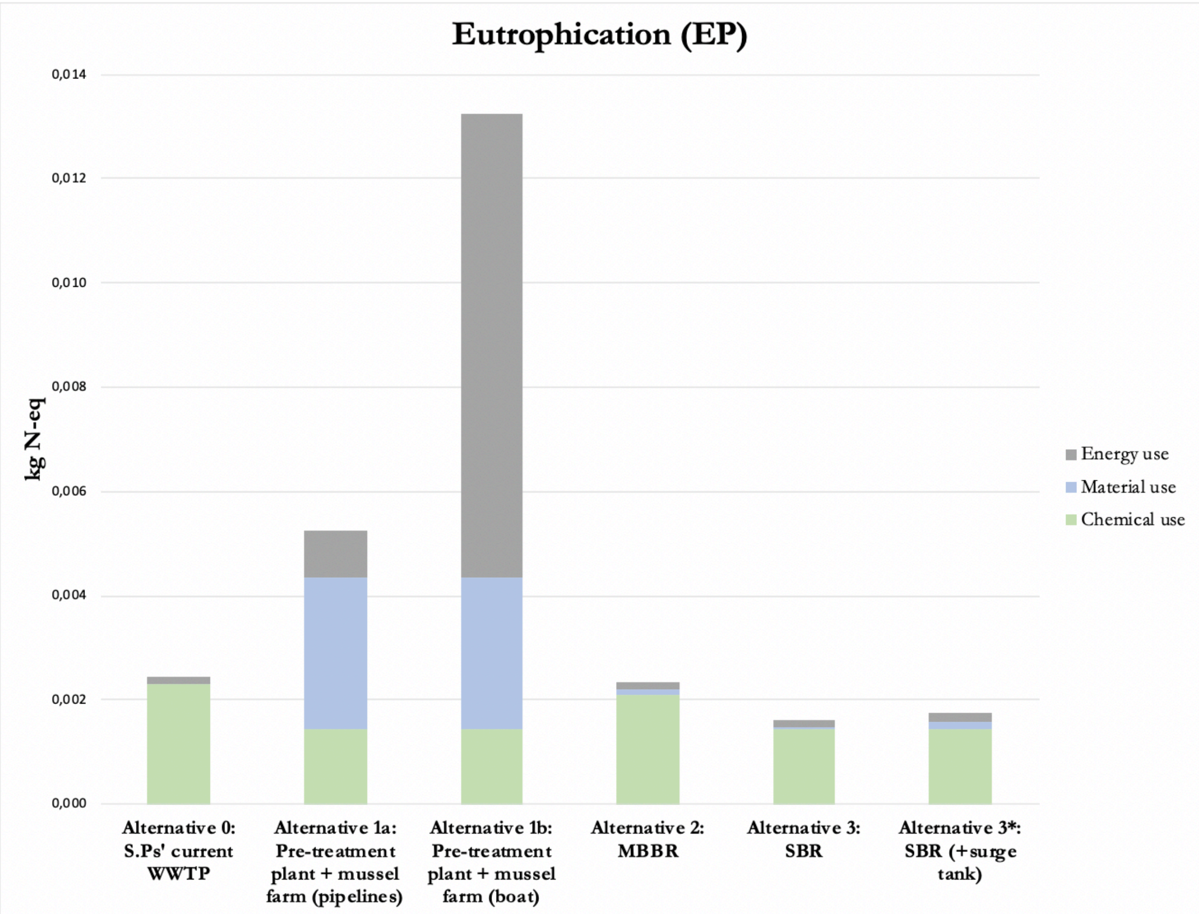

Figure 20. The eutrophication impact of kg N removed through the treatment, corresponding to 5600liter of treated process water for alternatives 0-3* and the share of energy, material and chemical use of total impact.

A detailed result presented in table 10, shows the share of chemical, energy and material use (%) for alternative 0-3* based on the eutrophication impact. Table 10 indicates that the chemical use is the greatest contributor for eutrophication impact, while the second largest contributor is energy use and lastly material use. As the results implies for all alternatives, except 1b - Pre-treatment plant + mussel farm (boat). Instead, the biggest contributor for eutrophication for alternative 1b - Pre-treatment plant + mussel farm (boat) is mainly energy use, followed by material and lastly chemical use.

Table 10. The share of chemical, energy and material consumption for alternatives 0-3* based on EP.

	Material use (%)	Chemical use (%)	Energy use (%)	Eutrophication
Alternative 0	0.050	95	5.0	0.0024
Alternative 1a	55	27	18	0.0049
Alternative 1b	22	11	67	0.0130
Alternative 2	5.0	89	6,0	0.0024
Alternative 3	2.6	90	8,0	0.0016
Alternative 3*	8.2	82	9.5	0.0017

To summarize the results of the global warming and eutrophication impact for all assessed alternatives, table 11 will present the degree of highest and lowest contributor to eutrophication and global warming.

Table 11. The degree of highest and lowest contributor to eutrophication and global warming of alternatives 0-3*. (Scale 1-6, where 6 is the lowest and 1 is the highest contributor).

	Global warming	**Eutrophication**
Alternative 0 - S.Ps' current WWTP	4	3 or 4
Alternative 1a - Pre-treatment plant + mussel farm (pipelines)	2	2
Alternative 1b - Pre-treatment plant + mussel farm (boat)	1	1
Alternative 2 - MBBR	3	3 or 4
Alternative 3 - SBR	6	6
Alternative 3* - SBR (+surge tank)	5	5

4.4 Overview of all proposed alternatives for Scandic Pelagic

This section is presenting a short evaluation, in order to get an overview of all proposed alternatives, including the excluded ones as well. Although, the purpose of this work did not include any economic or permission aspects, table 12 will present a short description and overview of the degree of permission, economic costs including the environmental assessment for all presented alternatives based on the current situation. As observed in table 12, the colors of red, yellow and green shows the degree of feasibility where red is least feasible, green most feasible and yellow somewhere in between. These results are mainly based on the results of this work and from an interview with S.P (2020-04-14).

Table 12. S.Ps' proposed alternatives, showing the degree of permission, economic costs and the environmental assessment of all suggested alternatives.

All alternatives	Permission	Economic cost	Environmental assessment
1a) An additional flotation tank, using pipelines for disposal to mussel farms.	No permit	High but reasonable costs	Reasonable
1b) An additional flotation tank, using boats for disposal to mussel farms.	No permit	High but reasonable costs	Reasonable
1c) An additional flotation tank, using pipelines to recipient.	No permit	Reasonable costs	Reasonable
1d) An additional flotation tank, using boats to recipient.	No permit	High but reasonable costs	Not reasonable
2) An additional flotation tank + MBBR technology + sedimentation, using pipelines for disposal to the recipient.	Possible	High costs	Reasonable
3) An additional flotation tank + SBR technology, using pipelines for disposal to recipient. The SBR technology, using pipelines for disposal to the recipient.	Possible	Reasonable costs	Reasonable
4) The Membrane bio reactor (MBR)	Permit possible	High costs	Reasonable

5a) An additional flotation tank + (small) MBBR technology, using pipelines for disposal to mussel farms.	Plausible	High costs, unreasonable costs	Reasonable
5b) An additional flotation tank + (small) MBBR technology, using boats for disposal to mussel farms	Plausible	High but reasonable costs	Reasonable

5 Discussion

Results show that alternatives 1b - Pre-treatment plant + mussel farm (boat) is the highest global warming and eutrophication contributor. Meanwhile, alternative 3 - SBR is the contributing least global warming and eutrophication impact. It is clear that chemical consumption is the greatest contributor to emissions for all assessed alternatives and for both impact categories studied, global warming and eutrophication. However, this is not the case for alternative 1b - Pre-treatment plant + mussel farm (boat) for the eutrophication impact, where energy use is the greatest contributor, followed by material and then chemical use in this case.

When interpreting the results of global warming impact, the second largest contributor was material use, closely followed by energy use for all assessed alternatives, except alternative 0 - SPs' current WWTP, which indicated the opposite, energy use was more important than material use. This exception can be explained by one of the assumptions that had to be made for this LCA study. As mentioned in chapter 3.4, the material construction of Ellös ARV was not included for the evaluation, only the required energy and chemical use for operating Ellös ARV. If the material use of Ellös ARV would be included, the same results as for the other evaluated alternatives would (most likely) imply for alternative 0 - S.Ps' current WWTP as well. Yet, it is still unsure whether or not alternative 0 - S.Ps' current WWTP still would be the 4th highest GW contributor but with a high probability generate into a higher contributor than currently shown in the results. This also explains the high share of chemical use for alternative 0 - S.Ps' current WWTP, which also has the highest share of chemical consumption among all assessed alternatives, as the material input for evaluation was significantly lower compared to the other parameters.

As observed in the results, alternative 1b - Pre-treatment plant + mussel farm (boat) was generating most global warming impact and alternative 2 - SBR was the lowest emission contributor. This is mainly due to the high amount of energy and materials required for alternative 1b - Pre-treatment plant + mussel farm (boat), compared to alternative 3 - SBR. Yet, as previously mentioned in chapter 3.4, the material construction of the boat was not included, meaning that alternative 1b - Mussel farm (boat) would even generate a higher impact value than currently showed in the results. When studying the material consumption of all assessed alternatives, the material consumption of alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat) is contributing a lot of emissions compared to the other alternatives (see table 9 and 10). The materials required for the mussel farms are the explanation for a larger share of material use and less by the pre-treatment plant operated on land. It is currently shown that alternative 1a - Pre-treatment plant + mussel farm (pipelines) has the highest material consumption followed by alternative 1b - Pre-treatment plant + mussel farm (boat). Yet, keeping in mind that data of material use for the boat, Stella Nova was not included in the results. Alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat) also have the lowest share of chemical consumption which is due to the relatively large amount of materials and energy required.

When comparing alternative 3 - SBR and alternative 3* - SBR (+surge tank), the proposal of possibly implementing an additional surge tank for alternative 3* would generate 5,9% higher GW impact compared to alternative 3 - SBR, which is mainly due to more energy and material required for this option. Alternative 2 - MBBR, is currently the 3rd greatest GW contributor and 3nd/4th greatest eutrophication contributor, meaning that alternative 2 - MBBR is currently the greatest emission contributor among the WWTPs operated on land. Accordingly, the MBBR technology is currently requiring most resources. As observed in figures 16-17, alternative 3 - SBR is generating lower environmental impact compared to alternative 2 - MMBR due to a lower chemical consumption of polyaluminumchloride (PAX). Since a greater amount of PAX is required in alternative 2 - MBBR, used in the flotation tank.

As seen in figure 20 and table 10, the results of eutrophication potential have also indicated that the chemical use is the biggest contributor to emissions for all assessed alternatives. But in this case, the second biggest contributor is energy use followed by material use, which was the opposite for the results of global warming impact. However, as previously mentioned, alternative 1b - Pre-treatment plant + mussel farm (boat) implies that the energy use for this approach is the greatest contributor, followed by material and then chemical use. As mentioned before, this is due to the extra energy consumption required (diesel fuel) for the boat, Stella Nova (see A.1).

When analyzing the results and observing table 10, alternative 2 - MBBR is the least environmentally friendly alternative based on the eutrophication (shared placed with alternative 0 - S.P current WWTP) and global warming results when comparing to the other WWTPs operated on land.

However, in order to evaluate the alternatives from an environmental point of view, the nutrient removal efficiency must be taken into account. As observed in table 3 presented in the results, alternative 2 - MBBR have among the highest nutrient removal efficiency levels of BOD and phosphorous and are among the alternatives with highest nitrogen removal efficiency levels. While alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat) have the lowest BOD removal efficiency levels but highest nitrogen and phosphorus removal efficiency levels among all. Alternative 0 - S.Ps' current WWTP has the lowest nitrogen removal efficiency level but among the alternatives with highest BOD and phosphorus removal efficiency levels. The low nitrogen removal efficiency level (only 25%) is due to the non-existing nitrogen purification requirement for S.P current WWTP. Yet, a correlation can be observed of the environmental impacts and the nutrient removal efficiency for this LCA. As mentioned in chapter 1.2, previous LCA studies regarding WWTPs have showed how higher nutrient removal efficiency levels have contributed to more emissions, due to the excessive amount of chemicals, energy and material use required in order to reduce as much organic matter in wastewater as possible. Which was confirmed by the LCA studies conducted by Foley and Rodriguez-Garcia et al (2009 resp 2011). Since the studies did included all parameters (energy, chemical and material use) in their work, the researchers could confirm that all parameters did increase in order to achieve higher nutrient removal efficiency levels.

Indeed, alternative 2 - MBBR has the highest nutrient removal efficiency due to the excessive amount of chemical and energy consumption among all WWTPs alternatives operated on land, but also contributing to most environmental impact. Since the previous LCA studies were conducted for conventional WWTPs, similar results could clearly be observed. Further indicating that there's a correlation between the amount of chemical and energy applied in the process.

As observed in tables 3-8, alternative 2 - MBBR, 3 - SBR and 3* - SBR (+ surge tank) are also the only conventional WWTPs that reach and surpass the average nutrient removal efficiency standards of WWTPs operating in Sweden. Alternative 0 - S.Ps' current WWTP is the least efficient and does not reach any of the average removal efficiency levels. Since this contradicts what the previous LCA studies have been reported. This alternative is also among the highest emission contributor among the assessed conventional WWTPs, but still have the lowest nitrogen removal efficiency among all.

Alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat), have the lowest chemical and energy consumption among the assessed alternatives. Which also explains the poor removal efficiency level of BOD and also confirmed by the LCA studies made by Foley and Rodriguez-Garcia et al (2009 resp 2011). Alternatives 1a and 1b are able to reduce more nitrogen than any assessed alternatives, due to mussel filtration and has a high nitrogen and phosphorus removal efficiency (100% resp 60-100%) because of that. However, mussel farms are not able to reduce any BOD and the presented removal efficiency levels of BOD (30-60%) for alternatives 1a and 1b is applied for the new proposed pre-treatment plant.

The findings in the LCA report conducted by Frösell and Karlsson (2019), did confirm that the biggest contributor for emissions of mussel farming were material and fuel use (within maintenance and harvesting activity) which is reflected in alternatives 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat) as well. The share and amount of material was significantly higher compared to the other assessed alternatives which also explains why these alternatives were among the highest contributor for global warming. Overall, in order to achieve a higher quality improvement of wastewater effluent, more chemical, energy and material use is required. Chemical and energy use are two important parameters that are highly correlated with the nutrient removal efficiency and easily adjustable in order to reduce available organic compounds in wastewater. Hence, the choice of energy and chemicals and how they are produced is significant important in the WWT process.

An interesting question based on this LCA study is which alternative should or is most preferable to implement from an environmental point of view? Clearly, multiple factors must take into account. Alternative 1a - Pre-treatment plant + mussel farm (pipeline) has indicated best potential for reducing nitrogen and phosphorus but is not sustainable based on the GW results and the nutrient removal efficiency levels of BOD. However, alternative 3 - SBR shows great potentials, since this alternative is currently generating lowest global warming and eutrophication impact among the proposed conventional WWTPs, at the same time, able to operate with high nutrient removal efficiency level.

5.1 Uncertainties

Due to several assumptions that were made for this work, some uncertainties regarding the results must be taken into account when interpreting the results.

First of all, the material construction of Ellös ARV and the boat could be included in order to achieve a more accurate result. As these values would mainly affect the results of alternative 0 - S.Ps' current WWTP and alternative 1b - Pre-treatment plant + mussel farm (boat). Alternative 0 - S.Ps' current WWTP would most likely have generated a higher global warming and eutrophication value than currently estimated and may resulted to a higher emission contributor than evaluated. Which can be applied for alternative 1b - Pre-treatment plant + mussel farm (boat) as well, since this option would most likely cause greater environmental impact than currently evaluated. Still, alternative 1b - Pre-treatment plant + mussel farm (boat) would probably still represent the greatest GW contributor. However, the inventory data (mainly material use) of Ellös ARV and the boat Stella Nova were excluded due to lack of data, time and because of the high uncertainties regarding the design construction of these. Data of these would require significantly more time for work in order to achieve a greater data collection but was not possible and way too complex for this type of work.

In addition, since the LCA results of the mussel farms were based on average impact values, could also affected the results of alternative 1a and 1b as well. If these values could fully be applied for S.P is not entirely certain.

As previously mentioned, the type of material for the construction components and total weight were chosen by the largest share of production material. For simplicity, not all materials could be included, and the non-dominant material use of the construction were excluded, therefore all assessed alternatives would most likely generate a greater environmental impact than presented. Since S.P did confirm how several construction components could be purchased re-used and the estimated lifespan of all material parts were based on its economic value, meaning that some components could probably be used for a significantly longer period than the currently set values and some perhaps less. The chemical use of Duramax-b1022 (a ceramic binder), used in all assessed alternatives were not included in the calculations. But since this certain chemical would be equally added in all assessed alternatives, the environmental impact would increase equally for all and wouldn't highly affect the presented results. The calculations for assessing the environmental impact were also highly dependent on the data in ecoinvent (v3) and were the best available match of data since the program continually updates and the latest data were used in this work.

The results were also based on the functional unit (kg N removed through the treatment, corresponding to 5600liter of treated process water), which was highly dependent on the produced amount wastewater and nitrogen from S.P. These values were based on average production values from 2017-2019 which clearly may vary from year to year.

When interpreting the nutrient removal efficiency levels of all assessed alternatives, some values may vary depending on certain conditions. For example, the mussel farm requires a certain marine condition, e.g. optimal salinity level and an optimal marine environment, to cultivate in order to achieve an optimal reduction efficiency of organic matter. This means that the mussel filtration may not always achieve a 100% reduction of nitrogen and phosphorus.

Finally, another important factor to keep in mind is that all assessed alternatives are in a development phase. S.Ps' goal is to implement one of the assessed alternatives by the end of 2021 and if needed room for adjustments to achieve a better result for the company and the environment is given. For instance, this LCA study has showed the importance of choice of chemical, energy and material use and how these may affect the environment and the nutrient removal efficiency levels of organic matter. S.P should therefore investigate which resources can either be reduced or eliminated from the WWT process without lowering any nutrient reduction levels. Also, if any construction components possible can be purchased re-used or substitute some of the current use chemicals with other chemicals with lower environmental impact but still able to meet the nutrient removal efficiency requirements.

6 Conclusions

To summarize the work and purpose of the research, the results have presented the environmental impact of global warming (kg CO_2-eq) and the eutrophication (kg N-eq) impacts based on the chosen functional unit (kg N removed through the treatment, corresponding to 5600liter of treated process water) of the assessed alternatives. As observed in the results, the proposed WWT alternative which is contributing highest GW is alternative 1b - Pre-treatment plant + mussel farm (boat) of 132kg CO_2-eq and the lowest contributor is alternative 3 - SBR of 61kg CO_2-eq. The mainly difference between alternative 1b - Pre-treatment plant + mussel farm (boat) and the other alternatives is the large share of material and energy use for alternative 1b and thereby results to a larger GW impact. However, chemical use contributes the largest share of GW impact for all assessed alternatives. Meaning that the chemical followed by material and then energy use should mainly be prioritized if companies are aiming for a GW reduction of their WWTP.

The highest contributor for eutrophication is currently alternative 1b - Pre-treatment plant + mussel farm (boat) of 0.013 kg N-eq while alternative 3 - SBR is the lowest contributor of 0.0016 kg N-eq. Since alternative 1b - Pre-treatment plant + mussel farm (boat) has a higher material and energy consumption in comparison to the other alternatives. The chemical use is still the important parameter to prioritize since this is also the biggest contributor for eutrophication and implies for all assessed alternatives (except alternative 1a and 1b - Pre-treatment plant + mussel farm (pipelines)/(boat), where the material use is the biggest contributor for these cases). If one of alternative 1a and 1b had to be implemented, alternative 1a - Pre-treatment plant + mussel farm (pipelines) are the best option from an environmental point of view. Since the results have indicated that the boat Stella Nova is contributing more environmental damage than pipelines.

A correlation between the nutrient removal efficiency and the environmental impacts has been observed. An increasement of chemical, material and energy use generate into a greater nutrient removal efficiency where this is reflected in the results and the previous LCA studies (made by Foley and Rodriguez-Garcia et al (2009 resp 2011)) presented in this work. When studying the conventional WWTPs operated on land, alternative 3 - MBBR is the highest emission contributor with 89 kg CO_2-eq resp 0.0024 kg N-eq. As previous mentioned, the lowest emission contributor among all was alternative 3 - SBR with 61kg CO_2-eq resp 0.0016 kg N-eq and still has a relatively high nutrient removal efficiency. Hence, the most environmentally friendly alternative to implement as a WWT strategy based on this LCA study.

Finally, the results have also showed the importance of choice and production of chemical, energy and materials use. Since these parameters highly affect the environment and the nutrient removal efficiency levels. For instance, S.P could do a further investigation if any chemicals or materials could be substitute with more environmentally friendly options or purchased re-used without lowering the nutrient removal requirements. All assessed alternatives are in a development phase and several adjustments can still be made in order to achieve a better environmental solution.

7 Future work

This work could be expanded further since several assumptions had to be made for this study in order to get a more accurate representation of the environmental impacts for the assessed WWT alternatives. This could be achieved by including currently not used data and achieve more precise information to base assumptions on. For instance, the lifespan of the material use, and the construction of Ellös ARV could be further investigated since these were approximately evaluated. As previous mentioned, not all proposed alternatives for S.P were evaluated in this work and a complete assessment and comparison might offer new results.

Future work investigating the economic perspective of different WWT alternatives might offer new conclusions. Since the economic aspect is a highly relevant parameter for all involved stakeholders and most likely will affect the decision-making on which alternative for treating wastewater should be implemented in the end. A further comparison of the economic and environmental aspects and the correlation between these parameters offers the possibility of further insights. Since a more environmentally friendly WWTP is strongly depended on the economic situation of a company.

During this work process, the legal process regarding the permissions for all proposed alternatives have been a highly discussed topic but are not evaluated further in this report. Hence, a deeper understanding of the legal permission process and the requirements for acquiring a permit for the alternatives would be another aspect to investigate in future work.

The functional unit (kg N removed through the treatment, corresponding to 5600liter of treated process water) for this work was one of many functional units considered and was chosen since this is one of the main goals for WWT processes. However, another interesting study would be to assess the phosphorous or BOD content in wastewater in future work. Meaning that an additional comparison, based on the same impact categories (global warming and eutrophication), between nitrogen, phosphors and BOD would be highly relevant and interesting for this type of LCA report.

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9 Appendix

Boat: Stella Nova			
	Value	**Unit**	**Comments**
Daily process water	450	m3/day	Produced from S.P
Fuel: Diesel	40	liter/km	Empty
Fuel: Diesel	60	liter/km	Full
Distance	6	km	From S.P to mussel farm
Transportations	3	times/day	Back and forth
Total distance with boat	36	km/day	
Total fuel consumption	300	liter/day	
Total fuel consumption	16992.78	liter/year	
Density: Diesel	0.832	kg/dm3	
Total weight: Diesel	14137.99	kg/year	

A.1. Inventory data and calculation of fuel consumption for the boat, Stella Nova used in alternative 1b - Pre-treatment plant + mussel farm (boat)

Average removal efficiency level (Sweden)	
Organic compound	**Removal efficiency level (%)**
Nitrogen	60-70
Phosphorus	90-95
BOD	95

A.2. Average removal efficiency levels of nitrogen, phosphorous and BOD in municipal sewage treatment in Sweden.

Energy consumption

Case	Source	Value	Unit
Alternative 0 - S.P current WWTP	Electricity	158872	kWh/year
Alternative 1a - Pre-tretment plant +mussel farm (pipelines)	Electricity	32400	kWh/year
Alternative 1a - Pre-treatment plant + mussel farm (boat)	Electricity	28800	kWh/year
	Diesel	16992	liter/year
Alternative 2 - MBBR	Electricity	183800	kWh/year
Alternative 3 - SBR	Electricity	160400	kWh/year
Alternative 3* - SBR (+surge tank)	Electricity	216400	kWh/year

A.3. Inventory data of energy consumption for alternatives 0-3* for reducing 1kg of nitrogen, corresponding to 5600liter of process water.

Chemical consumption

Case	Chemical	Value	Unit
Alternative 0 - S.P current WWTP	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	21000	l/year
	Polyacrylamides	19646,23	kg/year
Alternative 1a - Pre-treatment plant + mussel farm (pipelines)	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	21000	l/year
Alternative 1a - Pre-treatment plant + mussel farm (boat)	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	21000	l/year
Alternative 2 - MBBR	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	27372	l/year
Alternative 3 - SBR	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	21000	l/year
Alternative 3* - SBR (+surge tank)	Sulphuric acid	6000	l/year
	Sodium hydroxide	6000	l/year
	Polyaluminiumklorid (PAX)	21000	l/year

A.4. Inventory data of chemical consumption for alternatives 0-3* for reducing 1kg of nitrogen, corresponding to 5600liter of process water.

Material construction

Case	Part	Amount	Value (kg)	Condition	Material	Lifespan (years)
Alternative 0:	Flotation 1	1	750	EXISTING	Stainless steel	20
S.P current WWTP	Flotation 2	1	750	NEW	Stainless steel	20
(excluded: Ellös ARV)	Tank: Fish oil	1	500	NEW	Stainless steel	20
	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	Pipelines	1	10950	EXISTING	HDPE	20
Alternative 1a:	Flotation 1	1	750	EXISTING	Stainless steel	20
Pre-treatment plant +	Flotation 2	1	750	NEW	Stainless steel	20
mussel farm (pipelines)	Tank: Fish oil	1	500	NEW	Stainless steel	20
	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	Pipelines	1	10950	EXISTING	HDPE	20
	Mussel farm construction	1		NEW	Diffrent materials	
Alternative 1b:	Flotation 1	1	750	EXISTING	Stainless steel	20
Pre-treatment plant +	Flotation 2	1	750	NEW	Stainless steel	20
mussel farm (boat)	Tank: Fish oil	1	500	NEW	Stainless steel	20
(excluded: Stella Nova)	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	Pipelines	1	10950	EXISTING	HDPE	20
	Mussel farm construction	1		NEW	Diffrent materials	
Alternative 2:	Flotation 1	1	750	EXISTING	Stainless steel	20
MBBR	Flotation 2	1	750	NEW	Stainless steel	20
	Tank: Fish oil	1	500	NEW	Stainless steel	20
	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	MBBR reactor tank	1	329000	NEW	Concrete	20
	Reinforcing bar	1	80000	NEW	Kolstål	20
	Tank: Precipitate	1	165	REUSED	Steel	20
	Tank: Floculation	1	165	REUSED	Steel	20
	Sedimenteringbassäng	1	3000	REUSED	Steel	20
	Biocarriers: Anox Kaldnes K5	200m3	190000	NEW	HDPE	20
	Aluminium	1	100	NEW	Aluminium	20
	Pipelines	1	10950	EXISTING	HDPE	20
	Airblower	1	1500	NEW	Steel	15
Alternative 3:	Flotation 1	1	750	EXISTING	Stainless steel	20
SBR	Flotation 2	1	750	NEW	Stainless steel	20
	Tank: Fish oil	1	500	NEW	Stainless steel	20
	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	SBR reactor tank	1	658000	NEW	Concrete	20
	Reinforcing bar	1	160000	NEW	Steel	20
	Tank	1	115	NEW	HDPE	20
	Airblower	2	1500	NEW	Steel	15
	Pipelines	1	10950	EXISTING	HDPE	20
Alternative 3*:	Flotation 1	1	750	EXISTING	Stainless steel	20
SBR (+surge tank)	Flotation 2	1	750	NEW	Stainless steel	20
	Tank: Fish oil	1	500	NEW	Stainless steel	20
	Drumfilter	1	300	EXISTING	Steel	10 to 15
	Converyor belt	1	200	EXISTING	Steel	10 to 15
	SBR reactor tank	1	658000	NEW	Concrete	20
	Surge tank	1	350571	NEW	Concrete	20
	Reinforcing bar	1	160000	NEW	Steel	20
	Tank	1	115	NEW	HDPE	20
	Airblower	2	1500	NEW	Steel	15
	Pipelines	1	10950	EXISTING	HDPE	20

A.5. Inventory data of material construction of alternatives 0-3* for reducing 1kg of nitrogen, corresponding to 5600liter of process water.

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