Report

Environmental impacts of emerging salmon aquaculture technologies

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Abstract heading

This work is carried out as part of the project "Økt kunnskap om klima-, natur- og miljøpåvirkninger fra ulike produksjonsformer for laks" financed by Norwegian Seafood Research Fund, FHF (901833). The aim of the project is to evaluate the impact of different production technologies of salmon aquaculture on the climate, environment and nature and provide clear assessments of social and economic sustainability. This report focuses on screening life cycle assessments of the operation and infrastructure of different emerging technologies (traditional, closed, semi-closed, submerged, offshore, and land-based) and assessing their performance on selected indicators for estimating environmental impact. The major factors that contribute to negative environmental impact are identified and the performance of the technologies across different indicators are compared. Furthermore, the need for improved data availability for future assessments of these technologies is briefly discussed.

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List of abbreviations

AD – Abiotic depletion

AP – Acidification potential

CC – Climate change

CED – Cumulative energy demand

DM – Dry matter

eFCR - Economic feed conversion ratio

EP – Eutrophication potential

FEP – Freshwater eutrophication potential

FExP – Fresh water ecotoxicity potential

GHG – Greenhouse gas

GWP – Global warming potential

HTP – Human toxicity potential

LCA – Life cycle assessment

LCIA - Life cycle impact assessment

LW – Live weight

MEP – Marine eutrophication potential

MExP – Marine ecotoxicity potential

MTP - Marine toxicity potential

RAS – Recirculating aquaculture systems

TAP – Terrestrial acidification potential

Terminology and definitions

Concept	Abbreviation	Unit	Description
Global Warming Potential	GWP	kg CO_2-eq.	Indicates the global warming potential (GWP) due to emissions of GHG to air. Quantifies the integrated infrared radiative forcing increase of a GHG.
Terrestrial acidification	TAP	kg SO_2-eq.	Indicates the changes in acid deposition, following changes in air emission of NOx, NH_3 and SO_2 and the subsequent change in acidity in the soil due to a change in acid deposition.
Freshwater eutrophication	FEP	kg P-eq.	Indicates the enrichment of freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds.
Marine eutrophication	MEP	kg N-eq.	Indicates the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds
Marine and freshwater ecotoxicity	MExP FExP	1.4DCB-eq.	Indicates the potential impact on marine/freshwater organisms due to toxic substances emitted to the environment
Economic feed conversion ratio	eFCR	kg/kg	The amount of feed given to the fish divided by the biomass produced. eFCR also includes feed loss and feed given to fish that die during production. This differs from biological feed conversion ratio which refers to the amount eaten.
Live weight	LW	kg	The live weight of salmon before it has been slaughtered or prepared.

Executive summary

This work is carried out as part of the project "Økt kunnskap om klima-, natur- og miljøpåvirkninger fra ulike produksjonsformer for laks" financed by Norwegian Seafood Research Fund, FHF (901833). The project aims to evaluate the impact of different salmon aquaculture production technologies on the climate, environment and nature and provide an assessments of social and economic sustainability. The aim of this study, which is a screening life cycle assessment (LCA), is to quantify environmental impacts across multiple impact categories, in addition to the carbon footprint and to highlight the major differences between the production technologies. In addition, the study assesses how the design and operational differences among these technologies impact their environmental footprints. Further, based on the reported results, recommendations are proposed for processes or components, which should be closely monitored and reported in the future to reduce the uncertainty in further evaluations. The functional unit used is 1 kg live weight salmon at the farm gate.

The aquaculture production technologies evaluated here are the following: traditional, closed, semi-closed, submerged, offshore, and land-based. In the case of offshore and semi-closed technologies, two different concepts for each production technology were evaluated and, thus, the results are presented for each study case individually. The system boundary includes all the processes associated with the operations at aquaculture farms starting from smolt deployment and until the salmon is ready for harvest. As the focus of this particular study is on impacts associated with infrastructure and operations, the upstream impacts associated with feed production and transport are excluded.

The inventory data for this assessment is collected from the project's industry partners directly and supplemented with information from the literature. It should be noted that as these are emerging technologies in their pilot stage, knowledge and data gaps exist today. Thus, some assumptions were made in this study to provide some preliminary estimates on the potential environmental impacts from these different production technologies. Therefore, care must be taken to properly consider the assumptions before using or citing these results.

In this report we present preliminary results, which are subject to modification until the final project report.

Main findings from the report are as follows:

- The largest contributors to the negative environmental impacts across all technologies are mainly diesel consumption in vessels during the grow-out phase, on-farm electricity consumption, metal use in equipment and direct emissions of organic matter and other pollutants.
- Out of the eight technologies and concepts considered in this study, one of the semi-closed concepts has the lowest impacts in four of the seven impact categories assessed, while offshore technology has the highest impacts across five impact categories.
- When electricity is modelled with a European energy mix (i.e., containing a higher share of fossil energy than the Norwegian energy mix), land-based technology has the highest impact for global warming potential (GWP) due to a high electricity requirement.
- The environmental performance of traditional and submerged is quite similar although the latter performs slightly better in most impact categories, mainly due to a lower requirement for well boat's

operations (due to fewer lice treatments) as well as lower on-farm electricity consumption due to a more energy efficient feeding technology than the one commonly used in traditional technology.

- For marine eutrophication and ecotoxicity, closed and land-based technologies outperform traditional technology. This is primarily due to most sludge being collected instead of being released in the marine environment in the case of closed and land-based technologies.
- The environmental impacts for different concepts falling within the same aquaculture production technology (specifically, offshore, and semi-closed) exhibit large variation in environmental footprints due to their unique design and operational differences.

Figure 1 shows an overview of the relative environmental scores obtained for all production technologies across all seven impacts considered in this work. Within each impact category, the highest score (100%) denotes the technology with the highest impact across all eight cases evaluated, while the remaining seven scores are presented relative to this maximum one.

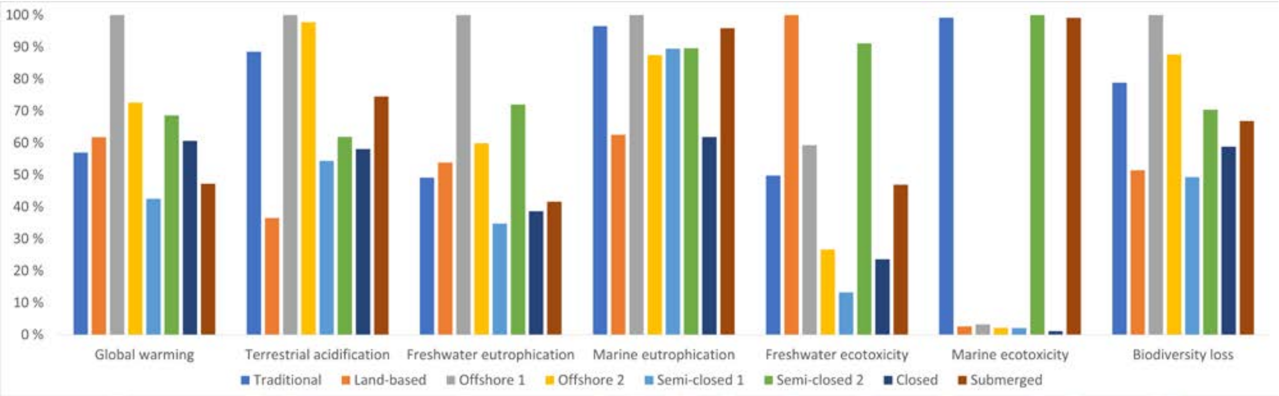


Figure 1: Overview of the relative potential impacts across the different categories for all technologies and study cases considered in the study. For each impact category, the results show the production technology with the highest score among all 8 cases evaluated, which corresponds to the maximum (100%) while the results for the other production technologies are provided in reference to this maximum. Offshore 1 and offshore 2 show the results for two different types of concepts within the offshore technology and likewise for semi-closed 1 and semi-closed 2.

In conclusion, the technologies with relatively lower energy and material consumption perform better in most impact categories except marine eutrophication which is associated with the direct release of sludge in the marine environment. On the other hand, technologies with the largest energy consumption, material requirements or sludge release in the marine environment have high impacts across most impact categories. The source of electricity is also a key factor in determining whether land-based technology has a higher GWP than offshore technology.

It must be emphasized that the results are based on preliminary data from a pilot study and many of the concepts are not yet fully optimized. However, this analysis points towards the major contributors of negative impacts and attempts to give a comparison of the environmental performance of the technologies. A more comprehensive assessment is needed to calculate the total footprint of salmon produced by each different technology.

There are some limitations of the study that should be noted. Diesel in vessels is a major driver for several impact categories, but vessel use is uncertain for these technologies and based on a number of assumptions for this analysis. Secondly, feed production and transport were considered outside the scope of this work. Feed for salmon constitutes a major contribution to all impact categories (for upstream impacts). The different technologies are reported to have a different economic feed conversion ratio, hence the scale of upstream impacts associated with feed will also be an important factor to consider in future assessments.

In addition, due to lack of primary data availability, some inputs (e.g., oxygen use during lice treatment, freshwater consumption, total seabed area affected) are not included. Future assessments may consider these differences.

Currently, semi-closed production technology only operates until the post-smolt stage, and the input parameters might change if the growth-phase is extended in the future until the harvest stage.

Another limitation is due to the LCA methodology, which uses global data and generic models for the quantification of impacts, and this may not capture the real site-specific impacts where these technologies are localized. The extent of negative environmental impacts may be different across locations due to site-specific environmental conditions and stressors (e.g. two facilities with the same emission quantities could have different impacts on the local environment depending on their geographical position). Thus, site-specific assessments and considerations are necessary for a comprehensive understanding of environmental impacts.

The results from this report will be used further in the project for assessing the environmental impact of salmon production in 2050 using different production technologies. These findings will be presented in the project's final report. The final report will consist of a holistic assessment of sustainability in scenarios defined within the project and will also include social and economic as well as environmental sustainability.

Norsk sammendrag

Dette arbeidet er utført som en del av prosjektet «Økt kunnskap om klima-, natur- og miljøpåvirkninger fra ulike produksjonsformer for laks» finansiert av Norges Sjømatforskningsfond, FHF (901833). Målet med prosjektet er å evaluere påvirkningen av ulike produksjonsteknologier for lakseoppdrett på klima, miljø og natur og gi klare vurderinger av sosial og økonomisk bærekraft. Denne studien er en screening LCA med et mål om å kvantifisere miljøpåvirkninger på tvers av flere påvirkningskategorier, i tillegg til karbonfotavtrykk og å synliggjøre de største forskjellene mellom produksjonsteknologiene. Målet er også å vurdere hvordan design- og driftsforskjellene mellom disse teknologiene påvirker deres miljøfotavtrykk. Funksjonelle enhet i analysen er 1 kg levende vekt laks før slakting. Et mål med dette arbeidet er også å identifisere hvilke prosesser som bør overvåkes og rapporteres nøye i fremtiden for å kunne gi mer nøyaktig resultater.

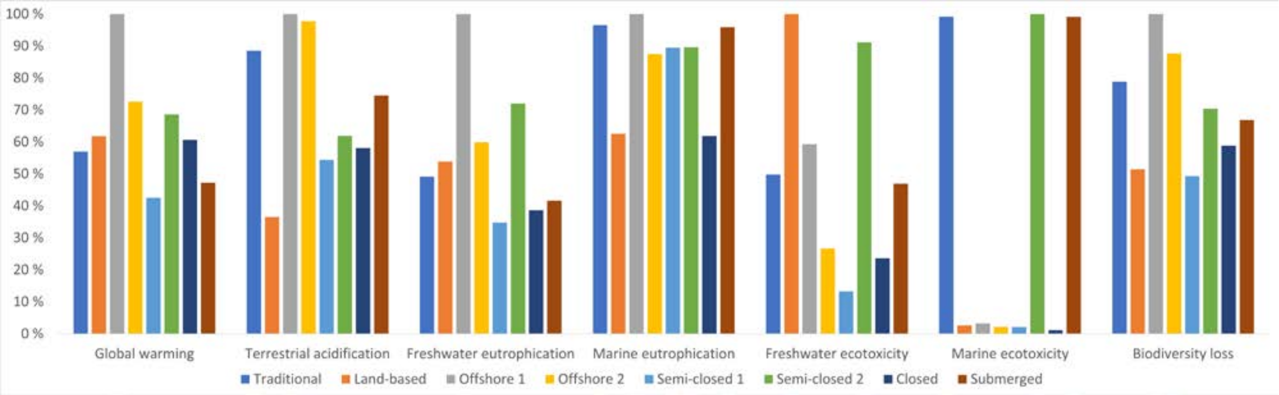
Produksjonsteknologiene som er evaluert her er følgende: tradisjonelle, lukkede, semi-lukkede, nedsenkbare, offshore og landbaserte. Når det gjelder offshore og semi-lukkede teknologier, ble to ulike konsepter for hver produksjonsteknologi evaluert og dermed presenteres resultatene for hver av disse konseptene individuelt. Systemgrensen omfatter alle prosesser knyttet til driften ved oppdrettsanlegg fra utsetting av smolt og til laksen er klar for slakting. Siden fokus hovedsakelig er på påvirkninger knyttet til infrastrukturen og driften, er påvirkningene knyttet til fôrproduksjon og transport utelatt.

Dataene for denne analysen er samlet inn direkte fra industripartnere i prosjektet og er supplert med verdier fra litteratur. Det bør bemerkes at ettersom dette er nye teknologier i pilotfaser, er produksjonsdata suboptimale for flere teknologier og det eksisterer et visst kunnskaps- og datagap i dag. På grunn av dette ble det gjort noen forutsetninger i denne studien for å gi noen foreløpige estimater på deres potensielle miljøpåvirkninger. Det er sannsynlig at resultatene fra denne studien vil kunne endre seg raskt ved videre utvikling av teknologiene. Resultatene bør dermed kun tolkes med alle antagelser og forutsetninger som er beskrevet i rapporten. Resultatene som presenteres i denne rapporten er foreløpige og endringer kan gjøres i prosjektets endelige rapport. Hovedfunnene fra rapporten er som følger:

- De største bidragsyterne til de negative miljøpåvirkningene på tvers av alle teknologier er hovedsakelig dieselforbruk, strømforbruk, metallbruk i utstyr og direkte utslipp av organisk materiale og forurensede stoffer.
- Av de 8 teknologiene og konseptene som ble vurdert i denne studien, har en av de semilukkede konseptene lavest påvirkning i fire av de syv påvirkningskategorier som er vurdert, mens offshoreteknologi har størst påvirkning på tvers av fem påvirkningskategorier.
- Når strømmiksen er modellert med en europeisk strømmiks som har et høyere bidrag fra fossile energikilder, har landbasert teknologi den største påvirkningen på globalt oppvarmings-potensiale (GWP) eller høyest karbonfotavtrykk.
- Miljøpåvirkningen fra tradisjonelle og nedsenkbare teknologier er ganske like, men nedsenkbar teknologi presterer litt bedre en tradisjonelt i de fleste påvirkningskategorier, hovedsakelig på grunn av et lavere behov for brønnbåter (på grunn av mindre lusebehandlinger) samt et lavere strømforbruk på på grunn av mer energieffektive fôringsoperasjoner enn ved tradisjonelt havbruk.

- Landbasert og lukket teknologi har lavere påvirkning på marin eutrofiering og økotoksisitet enn tradisjonell teknologi. Dette skyldes først og fremst at det meste av slammet samles opp i stedet for å slippes ut i det marine miljø ved lukket og landbasert teknologi.
- Det er en stor variasjon i miljøpåvirkningen fra ulike konsepter innenfor den samme produksjonsformen (offshore og semi-lukket) på grunn av variasjon i design og operasjon.

Figuren 1 under viser en oversikt over hvordan de ulike teknologier prestere på tvers av alle syv påvirkningskategoriene valgt i dette arbeidet.



Figur 1: Oversikt over de relative mulige påvirkningene på tvers av de forskjellige kategoriene for alle teknologier og studietilfeller vurdert i studien. Teknologien som har høyeste score vises med en maks 100% og alle andre teknologier vises med en referanse til maksimalt. Offshore 1 og offshore 2 viser resultatene for to ulike typer konsepter innen offshoreteknologien og likeledes for semi-lukket 1 og semi-lukket 2.

Konklusjonen er at teknologiene med relativt lavere energi- og materialforbruk presterer bedre i de fleste påvirkningskategorier bortsett fra marin eutrofiering som er knyttet til direkte utslipp av slam i det marine miljøet. Mens teknologiene som enten har høyest energibruk eller høyest materialbehov eller har utslipp av slam i det marine miljøet har høy påvirkning på tvers av de relevante påvirkningskategorier. Strømkilden er også en nøkkelfaktor for å avgjøre om landbasert teknologi har høyest klimagassutslipp enn offshore eller ikke.

Det må understrekes at resultatene er basert på data fra pilotstadiet og mange av konseptene er ennå ikke helt optimalisert. Imidlertid peker denne analysen mot de viktigste bidragsyterne til negative påvirkninger og forsøker å sammenligne av miljøpåvirkning fra teknologiene. En mer omfattende vurdering er nødvendig for å beregne det totale miljøfotavtrykket til laks produsert med ulike teknologier.

Det er noen begrensninger ved studien som bør noteres. Produksjon og forbrenning av diesel i arbeids båter og brønnbåter er en viktig driver til flere påvirkningskategorier. Samtidig er det usikkert hvilket behov de ulike produksjonsteknologiene vil ha for arbeids- og brønnbåter. I denne analysen har bruk av båter under produksjonsfasen først og fremst basert seg på grove estimater. For det andre ble fôrproduksjon og transport definert som utenfor rammen av dette arbeidet, og identifisert som en mangel siden fôr til laks er en stor bidragsyter til alle påvirkningskategorier for påvirkninger oppstrøms i verdikjeden. De ulike teknologiene har ulik økonomisk får faktor, og derfor vil påvirkning knyttet til fôr vil også være en viktig faktor i fremtidige analyser.

På grunn av mangel på data er enkelte innsatsfaktorer som oksygen under lusebehandling, ferskvannsforbruk, og totalt berørt havbunnsareal blant annet ikke inkludert. Fremtidige analyser kan vurdere å inkludere disse.

Det semi-lukkede systemet har per i dag har kun produksjon av post-smolt og ikke slakteklar fisk, og innsatsfaktorer kan endres dersom det produseres slakteklar fisk i semi-lukket i fremtiden.

En annen begrensning ved LCA-metodikken er at den bruker globale data og generiske modeller for kvantifisering av påvirkninger, og dette kan ikke fange opp den reelle effekten på de stedene der disse teknologiene er lokalisert i dag. Omfanget av negativ miljøpåvirkning kan være forskjellig i ulike regioner på grunn av ulike miljøforhold og stressfaktorer. F.eks. at 2 anlegg som har like mye utslipp vil kunne ha ulik påvirkning på miljøet avhengig av hvor de plasseres. Stedsspesifikke vurderinger og hensyn er derfor nødvendig for en helhetlig forståelse av miljøpåvirkninger på bestemte steder.

Resultatene fra denne rapporten vil bli brukt videre i prosjektet for å vurdere miljøpåvirkningen av lakseproduksjonen i 2050 med ulike produksjonsformene. Disse funnene vil bli presentert i prosjektets en sluttrapport som vil bestå av en helhetlig vurdering av bærekraft i scenarier definert i prosjektet og vil også inkludere sosialt og økonomisk dimensjonene av bærekraft.

1 Introduction

New aquaculture technologies for salmon production, such as offshore, land-based, and semi-closed might play a key role in ensuring future growth of the industry (PwC 2023) alongside traditional technologies. Nevertheless, there is a lack of knowledge on the environmental impacts of emerging aquaculture technologies other than greenhouse gas (GHG) emissions. Thus, an assessment of the environmental impacts along the value chain is needed.

The “traditional technology” referred to here is the use of open net pens used to produce grow-out of salmon in the sea. These pens can be either round or square, and it is common to have around 10 pens at each production site (Hognes and Skaar 2017). Most farmed salmon are currently produced with this technology.

Offshore aquaculture, also referred to as “open ocean” or “exposed” aquaculture, is an emerging approach to farm marine fish. It is increasingly regarded as one of the important means to ensure a sufficient and stable supply of seafood while minimizing the negative effects of conventional marine aquaculture on the environment of oceans (Froehlich et al. 2017). This technology can be used further from the coast in the open ocean, or closer to the coast, but in areas exposed to strong waves, wind, and currents.

“Semi-closed” or “closed” sea-based technology includes a barrier between the salmon and the surrounding ocean. This can be a complete barrier (closed technology) or partial barrier (semi-closed technology). There is no official definition of either technology, and it is mostly up to the producer to determine whether they are semi-closed or closed. There are great variations to the different concepts within the closed and semi-closed technologies. Rosten et al. (2013) suggest a categorization of closed technologies into four categories, where category 1 would only have a full or partial barrier surrounding the cage, and category 4 will have sludge collection and solutions to treat the inflow and outflow of water.

“Land-based technology” has mainly been used for smolt production, but several producers are producing grow-out salmon or post-smolt with this technology. Land-based technology includes three different types of technologies: recirculating aquaculture systems (RAS), flow-through systems, or hybrid systems (Bergheim et al. 2009). In RAS, most of the water used is recirculated, which in turn reduces the water consumption and decreases the emissions of nutrients (Dalsgaard et al. 2013). In all land-based technologies, there is treatment of the inflowing water, oxygen input, and collection of sludge. In our analysis, the land-based case is based on flow-through technology.

“Submerged technology” for aquaculture has existed since the 1970s and has lately become more commercially available for salmon production (Sievers et al. 2022). This production technology uses submersible net cages, which are suspended from the surface, can have adjustable buoyancy, and may be rigid or flexible (Warren-Myers et al. 2022). Submerged net bags are fitted in a solid and rugged frame and submerged under the water.

This report focuses on quantifying the environmental impacts of producing 1 kg salmon at the farm gate with the aforementioned production technologies. In the case of offshore and semi-closed technologies, two different concepts for each production technology are evaluated and, thus, the results are presented for each study case individually. It is important to note that as emerging technologies advance, there may be rapid developments that can have a great impact on the findings presented in this report, such as lower energy consumption or better production with less mortality.

The results will be further used in evaluating the environmental performance of the different technologies in a set of future scenarios and provide an initial knowledge base for policy incentives for future growth of the industry. These preliminary results may be updated in the project's final report.

1.1 Literature review

There are a number of articles, reports and master theses that have conducted life cycle assessments (LCA) on traditional and new production technologies of salmon in Norway (N. W. Ayer and Tyedmers 2009; Pelletier et al. 2009; Ziegler et al. 2013; Nyhus 2014; Nistad 2020; Ziegler et al. 2021; Bjørshoel and Shariff 2022; Johansen et al. 2022). Two master's theses have assessed energy use and environmental impacts of smolt production in RAS (Bjørshoel and Shariff 2022; Nistad 2020) and one has assessed production with closed technology in the sea (Nyhus 2014). There are several review articles on LCAs of aquaculture production technologies in different countries and for different species (Ghamkhar et al. 2021; Henriksson et al. 2013; Philis et al. 2019).

SINTEF has led three projects financed by the Norwegian Seafood Research Fund (FHF), where the carbon footprint of Norwegian Atlantic salmon was calculated (Johansen et al. 2022; Ziegler et al. 2013, 2021). The latest report was published in 2022, and found that for salmon produced in traditional cages the carbon footprint is 3.8 kg CO_2-eq. at the farm gate including feed (Johansen et al. 2022). Feed accounted for approximately 75% of the total carbon footprint. The latest report also included simplified scenarios for production in closed cages at sea, post-smolt produced on land, and grow-out production in either an offshore system or in a traditional farm. Production in closed cages led to an estimated reduction of 12% of the carbon footprint for 1 kg per head on gutted salmon sold in Paris. Production of post-smolt increased the carbon footprint by 24% (if the grow out phase happened using the offshore technology) and with 3% if the grow-out phase was in a traditional cage. Other technologies for salmon farming were not included. A longer production phase on land (with post-smolt) reduced the emissions related to feed due to a lower feed conversion ratio using the land-based technology. Emissions related to infrastructure increased in the scenario where the grow out-fish was produced in offshore technology.

Philis et al. (2019) conducted a review of original studies of LCAs of aquaculture production technologies including closed sea-based systems, land-based systems, and open net pens (traditional farms). The case studies included several species, i.e. salmon, trout and arctic char, and aquaculture production in different countries such as Norway, Canada, Peru, Chile, the U.S., France, Sweden, and Scotland. The studies reviewed in Philis et al. (2019) also used different characterization methodologies, and neither the system boundaries nor the functional units were equal across the studies. This represents an important limitation towards comparing these systems. Most studies used CML-IA, followed by ReCiPe midpoint indicators as a methodological approach. Many of the studies evaluated the impact on global warming potential (GWP), eutrophication potential (EP), acidification potential (AP) and cumulative energy demand (CED). Philis et al. (2019) summarized the results from the studies for these four categories and found that land-based systems had the highest contributions to GWP and AP while open systems had the highest EP. They also reported that land-based systems require more CED than closed and traditional technologies.

In another review article, Ghamkhar et al. (2021) analysed 18 LCA studies with environmental assessments of land-based RAS and flow-through systems, net cages, and pond systems. They analyzed feed, energy and infrastructure for the impact categories land use, water use and EP. They found that intensive production in a land-based technology has the potential to reduce water consumption and nutrient emissions - with higher energy consumption. Therefore, environmental impacts are highly dependent on the electricity mix used, which may cause a burden shift to, for example, higher carbon emissions if the electricity is generated from fossil fuels.

Henriksson et al. (2013) assessed 10 LCA studies. Similar to Philis et al. (2019) and Ghamkhar et al. (2021), they compared production technologies across countries and species. The functional unit in their study is 1-ton LW fish, and they compare the different technologies with regards to GWP and CED. There is also an overlap of the LCAs reviewed in Philis et al. (2019), Henriksson et al. (2013) and Ghamkar et al. (2021).

McGrath et al. (2015) performed a LCA of Chinook Salmon in a closed containment technology, based on actual input parameters and data for an ideal operation. Feed was the highest contributing process to all impact categories except marine eutrophication potential (MEP). According to their findings, infrastructure and energy use were the major contributors to GWP, when excluding feed. On-site emissions of nitrogen contributed the most to MEP.

Ayer and Tyedmers (2009) employed LCA to compare production of 1 ton of salmon and Arctic char each in Canada with a closed sea-based technology, and land-based RAS with a flow-through system. For all the impact categories assessed (GWP, abiotic depletion - AD, human toxicity potential - HTP, marine toxicity potential (MTP), AP, and EP), land-based RAS technology had the highest contribution except for EP. The contribution was mainly due to energy consumption, which was assumed to be attributed to coal-generated electricity constituting 80% of energy consumption. Even in a sensitivity analysis of energy carriers where all the included technologies operated on the same electricity mix (61% hydro, 18% coal, 4% oil and 4% natural gas), the land-based RAS system dominated in all impact categories except for eutrophication.

Liu et al. (2016) compared two farming production technologies for Atlantic salmon: open net production in Norway and land-based production of RAS in the U.S. They found that the carbon footprint (reported as GWP) was twice as high for the land-based production. However, the main driver was the electricity use, which was an U.S. electricity mix.

Bergman et al. (2020) investigated the environmental performance of a commercial land-based RAS farm of a tropical finfish and a crustacean species in a Swedish production facility. They used a cradle-to-gate approach. The environmental impact categories considered were FEP, GWP, energy demand, land use, and dependency on animal-source feed inputs. The functional unit in their study was 1 kg of fillets without skin of Nile tilapia (Oreochromis niloticus) and African Clarias catfish (Clarias gariepinus) (excluding packaging). The system boundary included fry production, transportation of fry, grow-out in a RAS as well as on-site slaughtering and hand filleting of fish. Feed production contributed the most to all environmental impacts (with reported shares of between 67- 98%) except for the energy demand for tilapia production.

The environmental performance of sea bream and sea bass production in Mediterranean aquaculture was estimated by Kallitsis et al. (2020) for different indicators such as GWP, AP, ozone depletion potential, AD, photochemical oxidant creation potential, terrestrial ecotoxicity potential, marine aquatic ecotoxicity potential, HTP and EP. The electricity mix, material requirements and background processes reflected the Greek market. The system boundary included fish feed production and the rearing operation, as well as the packaging and delivery processes. Feed production was reported as the most intensive process throughout the life cycle across multiple impact categories. Packaging and delivery processes contributed to approximately 40% of the GWP impacts, while rearing stage was the main driver for the high eutrophication impacts.

Zoli et al. (2023) quantified the environmental impacts of two fish species, namely European sea bass and gilthead sea bream in an offshore production facility in Italy. Their study used a cradle-to-gate approach with a functional unit of 1 ton of fish at harvest size. Their system boundary included the juveniles supply, feed production, feed supply (e.g., agricultural processes for plant-based ingredients, wild fisheries for marine based protein, transport), and farm management (feed distribution, fish monitoring and harvest). Similar to previous studies, they identified feed as the main hotspot for environmental impacts with contributions of at least 60% in all impact categories, except for marine eutrophication, which is driven by nutrient emissions.

Bohnes and Laurent (2021) evaluated the environmental impacts of 8 different aquaculture production systems in Singapore for years 2017 and 2040. Their analysis assessed the impacts associated with four fish and seafood products (marine fishes, freshwater fishes, mollusks, and crustaceans) and four technologies: low technology (which require limited energy inputs and low technical knowledge of the farmer), high technology (which demand more complex infrastructures, techniques, and usually important financial investments), RAS, and offshore. They reported results for 11 impact categories: climate change-short term, acidification, eutrophication, human toxicity cancer, human toxicity non-cancer, water scarcity, freshwater ecotoxicity, fossil and nuclear energy use, mineral resources use, land competition and net primary production use. Overall, per unit of edible seafood produced, the study found production of marine fish in sea cages near-shore and in RAS to be the most attractive options to limit the environmental impacts while increasing seafood production in Singapore.

Previous studies comparing different production technologies in aquaculture usually consider one or two production technologies or review articles that compare several production technologies based on studies from different countries and for different species which in general have different system boundaries, functional units and even impact assessment methodologies. There is a need for an assessment of these production technologies operating with the same species (e.g. Atlantic salmon) in the same country (e.g. Norway), and with the same system boundaries and functional units.

2 Methodology

2.1 Aim and project organization

The aim of the report is to identify the major differences in impacts associated with producing salmon using different technologies, both traditional and emerging ones. A full description of the goal and scope of the report is given in section 2.2. This study was funded by FHF (901833). The work is carried out through collaboration between SINTEF Ocean AS and industry partners operating as aquaculture farmers and equipment suppliers. A reference group of experts has provided feedback on the work. This study was carried out between February 2023 and 2024.

2.2 Goal and scope

The main goal of the work is to estimate the potential environmental impacts of a set of different types of technologies for salmon aquaculture across multiple impact categories, in addition to the GWP. Furthermore, the study assesses how the design and operational differences among these technologies impact their environmental footprints. The functional unit used is 1 kg LW salmon at the farm gate. The methodology applied in this study is a screening LCA of traditional and emerging technologies in salmon aquaculture.

The study focuses on the main differences between the production technologies; therefore, the results will not be representative of all concepts falling within the same technology. It highlights major differences between the production technologies and shows where the impacts are the greatest for each production system. The identified processes should be closely monitored and reported in the future to improve the uncertainty in further evaluations.

Table 1: Overview of processes included in the assessment for each technology. The abbreviations in the caption refer to the production technologies, thus, "T" is Traditional, "L" is land-based, "O1" is offshore 1, "O2" is offshore 2, "SC1" is semi-closed 1, "SC2" is semi-closed 2, "C" is closed and "S" is for submerged production technology.

Process	Sub-process	T	L	O1	O2	SC1	SC2	C	S
Energy	Diesel in service boats	X	-	X	X	X	X	X	X
	Diesel in well boats	X	X	X	X	X	X	X	X
	Electricity	X	X	X	X	X	X	X	X
Chemical and veterinary treatment	Lice treatment	X	-	-	X	-	-	-	-
	Oxygen	-	-	-	-	-	X	-	-
Regular smolt production in RAS	Electricity	X	X	X	-	X	X	X	X
	Chemicals (oxygen and hydrogen peroxide)	X	X	X	-	X	X	X	X
	Area	X	X	X	-	X	X	X	X
Large smolt production in RAS	Electricity	-	-	-	X	-	-	-	-
	Chemicals (oxygen and hydrogen peroxide)	-	-	-	X	-	-	-	-
	Area	-	-	-	X	-	-	-	-
Large smolt production in traditional system	Electricity	-	-	X	-	-	-	-	-
Treatment of effluents	Electricity for drying sludge	-	X	-	-	-	-	-	-
	Sludge to biogas*	-	X	-	-	-	-	X	-
	Acids for storage dead fish	X	X	X	X	X	X	X	X
	Incineration of dead fish*	X	X	X	X	X	X	X	X
Transport	Transport infrastructure	X	X		X	X	X	X	X
	Transport of sludge	-	X	-	-	-	-	X	-
	Transport of dead fish	X	X	X	X	X	X	X	X
Infrastructure	Materials (steel, plastic, concrete)	X	X	X	X	X	X	X	X
	Recycling of materials	-	-	-	-	-	-	-	-
	Area	-	-	-	-	-	-	-	-
Equipment	ROV, Camera, Water pumps	-	-	-	-	-	-	-	-
Direct emissions	Emissions from sludge (feed loss and feces)	X	X	X	X	X	X	X	X
	Emissions from antifouling paint	-	-	-	-	-	-	-	-
	Emissions from nets (Cu)	X	-	-	-	-	X	-	X

*Sludge to biogas and incineration of dead fish are not included in the base case.

The following technologies are included in the assessment: traditional, land-based, offshore, semi-closed, closed and submerged. A description of the technologies is given in section 2.4. For some of these technologies, the assessment is based on one concept, while for others (offshore and semi-closed) two concepts are assessed. The system boundary includes all the processes associated with the operations at aquaculture farms starting from smolt deployment and until the salmon is ready for harvest. As the focus is mainly on impacts associated with the infrastructure and operations, the upstream impacts associated with feed production and transport are excluded. Table 1 provides an overview of the processes included and excluded in the assessment of each technology.

Impact assessment method: For impact assessment, the ReCiPe 2016 Midpoint (Hierarchist) V1.06 / World (2010) H method is used, which includes 17 midpoint impact categories. The LCA models are built in the software SimaPro Developer MultiUser version 9.3.0.3 using Ecoinvent v 3.8 (Ecoinvent, 2021) (cut off by classification) for water and land transports, energy and fuels usage, materials, chemicals, and infrastructure. For the quantification of damage to the area of protection ecosystem quality, the ReCiPe 2016 Endpoint (Hierarchist) V1.06 / World (2010) H method is used.

Impact categories: An impact category groups different emissions into one effect on the environment by making use of characterization factors. Midpoint characterization factors quantify impacts at an intermediary step in the cause-effect chain and are usually indicated in emission or resource use equivalents (e.g., CO_2-eq., SO_2-eq., etc.). The impact categories considered in this work are the most common ones reported in assessments of food systems: climate change, terrestrial acidification, marine and freshwater eutrophication and respectively, ecotoxicity.

- *Climate change:* indicates the GWP due to emissions of GHG to air. Quantifies the integrated infrared radiative forcing increase of a GHG. It is expressed in kg CO_2-equivalents.

- *Terrestrial acidification:* models the fate of acidifying pollutants in the atmosphere and in the soil. TAP is expressed in kg SO_2-equivalents and consider the changes in acid deposition, following changes in air emission of NOx, NH_3 and SO_2 and the subsequent change in acidity in the soil due to a change in acid deposition.

- *Freshwater eutrophication:* indicator for the enrichment of freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds. FEP is expressed in kg P to freshwater-equivalents.

- *Marine eutrophication:* indicates the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds. MEP are expressed in kg N-equivalents.

- *Marine and freshwater ecotoxicity:* indicates the potential impact on marine/freshwater organisms due to toxic substances emitted to the environment. MExP as well as FExP are both expressed in kg 1.4-dichlorobenzene-equivalents (1.4DCB-eq.).

Ecosystem quality: For the conversion of environmental pressures to biodiversity impacts, the life cycle impact assessment (LCIA) method ReCiPe 2016 Endpoint (Huijbregts et al. 2016) was chosen to be consistent with the method used for the midpoint results. The endpoint characterization factors quantify the consequence of an anthropogenic intervention on three areas of protection: ecosystem quality, human health, or resource use. The estimated endpoint in this study are impacts related to ecosystem quality only, namely biodiversity losses associated with production of 1 kg of salmon at the farm gate under the different production technologies. Caution should be taken when interpreting these results as the term biodiversity within the LCA framework refers to species richness (losses of it) and does not cover other aspects of, for example, species abundances, genetic variance. Species richness is one of the most common indicators to measure the damage to diversity and is described as the fraction of species that can potentially be lost in comparison with a natural or undisturbed area. In the ReCiPe 2016 method, the metric used for reporting the impacts on biodiversity loss is the time-integrated number of species lost (species.yr). The biodiversity impact model, which the ReCiPe method uses for quantifying impacts on biodiversity loss, translates the inventory flows to meaningful indicators that describe their influence on twelve impact categories: global warming (terrestrial & freshwater ecosystems), ozone formation (terrestrial ecosystems), terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, marine ecotoxicity, freshwater ecotoxicity, land use, and water consumption (terrestrial & aquatic ecosystems).

2.3 Data collection

The inventory data for this assessment was collected from the project's industry partners directly and supplemented with information from the literature. Appendix 1 presents a request for data inventory, which was sent out to all industry partners. Due to confidentiality agreements, only information on the inventory parameters based on values from the literature is provided. The data received through the direct communication with partners forms the basis for this assessment, nevertheless for some processes such as diesel used in vessels, transportation distances for infrastructure, sludge, dead fish, and emissions to the marine and freshwater environment, additional information were collected from reports or the scientific literature. Data from industry partners was collected through the inventory request form from Appendix 1, in addition to a value chain validation form. A complete overview of the formulas and parameters used from the literature is given further in the next sections of this chapter.

2.4 Production technologies and value chains

Farmed salmon has a production cycle that is divided into a freshwater phase and a seawater phase and lasts approximately 3 years. Smolt production happens in land-based facilities, either RAS, flow-through or hybrid technology, and uses freshwater. Smolt metamorphoses into saltwater fish, and either the grow-out phase or the post-smolt production begins. The grow-out stage is in saltwater. The size is usually 70-150 g at this stage, but several producers are starting to produce smolt up to 500 g and post-smolt up to 1 kg to reduce the production phase in the sea (Hernes 2022). The production cycle is not the same for the different production technologies. Figure 2 presents alternative production cycles and strategies. In submerged, land-based, closed, and semi-closed technologies, the production cycle can be the same as in traditional cages with the production of smolt followed by production of grow-out fish. However, all these technologies, including traditional, can also be used to produce post-smolt for grow-out production in either traditional, submerged, or offshore technologies. In offshore farms, it can be beneficial to use post-smolt as the conditions are often rougher with stronger wind, waves, and currents. Producing post-smolt in land-based, closed, semi-closed or submerged technologies can be beneficial to reduce sea lice treatments when the salmon is young and most vulnerable.

Figure 2: Alternative production cycles for farmed salmon. The figure is based on Tveterås et al. (2020) and industry information.

In this analysis, smolt production and the production of salmon is included in all the production systems. However, it is important to note that the results are not directly comparable as the production cycles vary. Within the same production technology there are different concepts in addition to multiple options for the different activities within the value chain such as sludge collection, production of grow-out fish or post-smolt, treatment of input and wastewater.

Figure 3 shows the value chain for traditional, closed, semi-closed, submerged, and offshore production technologies. Collection of sludge in traditional, closed, semi-closed and submerged technologies is possible, but it is currently only the norm in closed technology. The sections below provide a brief description of production technologies and their differences. The value chain of production with land-based technology is shown in Figure 4. The inputs used in our analysis are represented by the orange boxes in the figures and are further explained in the following sections.

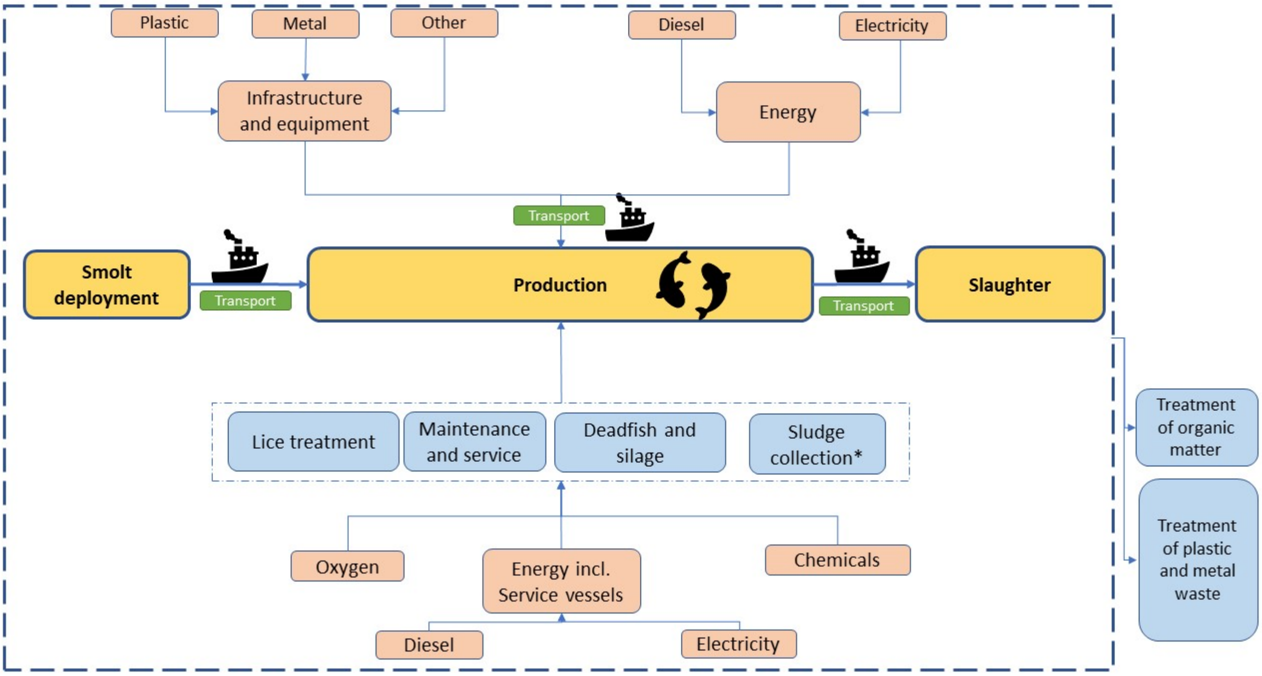


Figure 3: Generic description of value chain and input factors included in our analysis of traditional, (semi-) closed, submerged and offshore production technologies. The yellow boxes show the main processes, the orange boxes represent the input factors, the blue boxes show services or activities on-site at the farms and the green boxes represent the transport. *Sludge collection is currently only done in closed technology, though there exist options for this for traditional, submerged, and semi-closed technologies as well.

2.4.1 Traditional production technology

The production cycle in traditional systems is either from smolt (100-150 g weight at deployment) until slaughter (or from post-smolt to slaughter). There is usually no collection of sludge in traditional production systems, even though technological solutions for this exist[1]. The energy carriers are either electricity or diesel (burnt in generators). In this study, for the traditional technology it is assumed a fully electrified production cycle from smolt to slaughter with no sludge collection.

2.4.2 Submerged production technology

The submerged technology is similar to the traditional technology, but has the possibility to descend the fish deeper in the water to avoid sea lice (Warren-Myers et al. 2022). Such production facilities have a plastic dome, where the fish can get air whilst the system is submerged. Submerged systems also use waterborne-based feeding, which uses less energy than airborne feeding, and reduces the emissions of microplastics due to less wear and tear.

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[1] https://www.framo.com/no/aquaculture/liftup/

2.4.3 Semi-closed and closed production technology

Semi-closed or closed technology can be used to produce post-smolt (up to 500-1500 g) and grow-out fish. Some semi-closed systems have technical solutions to collect sludge, but it is not common or required to do so. Semi-closed systems have a physical barrier between the fish and the environment but allow the water to flow through the system. The barrier can be a rigid or flexible structure. In this work, two different semi-closed systems are modelled that also have different production cycles and different input factors, where one system uses oxygen, and the other does not.

Some concepts pump cold water from the depths, where there is usually less sea lice, as the amount of sea lice decreases with depth (Oppedal et al. 2017). Some concepts treat the inlet water, whereas other concepts do not do any filtering or cleansing of the inlet water (SARF 2019). In systems with less circulation of water, more oxygen inputs are required. For some flow-through concepts, added oxygen is not required.

In this work it is assumed that all closed systems collect sludge using mechanical filters. Closed systems have a barrier between the fish and some producers clean the input water as well. In a closed system, there is also an input of oxygen. In this report, one closed system with sludge collection and supplemental oxygen, one flow-through semi-closed technology without supplemental oxygen (semi-closed 1), and one semi-closed with oxygen use (semi-closed 2) are included.

2.4.4 Offshore production technology

In an offshore technology, it is common to use post-smolt (500-1500 g) and grow fish until slaughter weight. Since offshore systems are made to withhold harsher environments, the structure of these systems is more robust than traditional systems. This also means that the material use is substantially higher.

2.4.5 Land-based production technology

In land-based production technology (Figure 4), the whole production cycle takes place on land in either RAS, in a flow through system, or in a hybrid system. The main difference between these systems is that in RAS, up to 99% water is being recirculated (AKVA Group 2022), whereas in flow-through system the water is not reused. These technologies are usually used to produce smolt and post-smolt, but in this study reference is made to the production of grow-out fish in land-based systems. In this study, the land-based technology is based on a flow-through system and an inventory for infrastructure was based on the available literature.

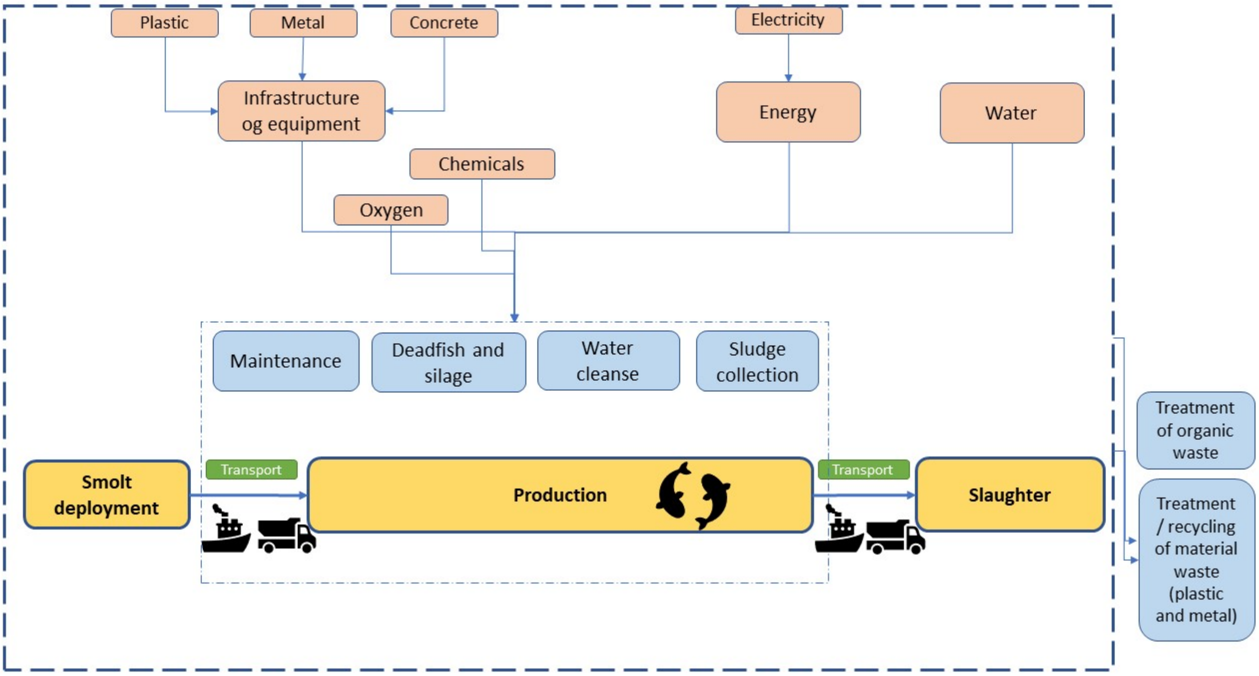

Figure 4: Description of the value chain and input factors included in our analysis of the land-based production system. The yellow boxes show the main processes, the orange boxes represent the input factors, the blue boxes show services or activities on-site at the farms and the green boxes represent the transport.

2.5 Smolt production

Production of smolt includes electricity use, area use, and the input of sodium hydroxide. It is assumed here that the smolt process is the same for all production systems, but since the size of smolt at deployment varies, in this work two smolt processes were modelled: regular smolt and large smolt.

For regular smolt, the size of smolt is in the range of 70-150 g. According to Iversen & Hermansen (2019), the average weight of smolt at deployment is 130 g. Electricity consumption was assumed as 8.5 kWh per kg smolt produced and diesel use 0.01 kg per kg smolt produced based on Nistad et al. (2021) and Johansen et al. (2022). The latter also uses an oxygen input of 0.5-1 kg per kg produced smolt, based on industry information. There is also an input of acids and sodium hydroxide of 1.4 g and 0.2 kg smolt produced based on Johansen et al. (2022). Brown et al. (2022) indicates that economic feed conversion ratio (eFCR) for smolt production is the same as for grow out phase. According to the Directorate of Fisheries, average eFCR for salmon production in Norway is 1.3. However, based on industry information, Johansen et al (2022) uses an eFCR of 1 for smolt.

Large smolt is defined in our model as smolt of 150 – 1000 g at deployment. Electricity used per kg smolt produced is estimated as 8.8 kWh per kg smolt produced (Nistad 2020) is based on an energy model of post-smolt in land-based RAS facilities.

Area use is based on an assumption that smolt production facilities have a lifetime of 20 years (Johansen et al. 2022), and that the area required per kg smolt is 0.022-0.029 m^2 for regular smolt (Nistad 2020) and 2.3 m^2 for large smolt (Hilmarsen et al. 2018). Over the whole lifetime of the production facility, the area used per kg of smolt produced is then 0.0013 m^2 for regular smolt and 0.125 m^2 for large smolt.

Equation 1 is used to calculate input of smolt per kilo salmon live weight at harvest:

$$\frac{\textit{smolt weight at deployment} \times (1 + \textit{mortality rate})}{\textit{Salmon weight at slaughter}} = \textit{input of kg smolt per kg salmon produced} \quad (1)$$

If, for example, smolt weight at deployment is 130 g, the mortality rate (as the number of dead salmon throughout a production cycle) is 10% and the weight of salmon at slaughter is 4.5 kg, the input of smolt is 32 g per kg salmon produced, as shown in the equation 2.

$$\frac{0.13\ kg \times (1+0.10)}{4.50\ kg} = 0.032\ kg/kg \quad (2)$$

This value is comparable to literature: Johansen et al. (2022), used an input of 34 g smolt per kg salmon produced.

2.6 Vessels

The system boundaries include production, distribution, and combustion of diesel used in service and well boats. These activities are modelled in this study using two Ecoinvent processes reflecting the global market (see Appendix 2). Information on vessel use is based on industry information and data from the literature. Nistad et al. (2021) mapped fuel use for vessels for traditional farms (see Table 2). In this study, these numbers are combined with primary data from industry to estimate the fuel use of vessels for all technologies and concepts assessed.

Table 2: Fuel use for well boats, service vessels and smaller working vessels based on Nistad et al. (2021).

Type of boat	L diesel / kg LW salmon
Well boat	0.08
Larger working vessels	0.015
Service vessel >15 m	0.008
Service vessel < 15 m	0.02
Smaller working vessels	0.007
Total fuel use	0.13

The vessel use for the different production technologies is based on Nistad et al. (2021) and inputs from the industry (Table 3). Based on industry inputs for this project, the use of well boats for some land-based systems has been included. It is assumed that both submerged and semi-closed technology will have less use for well boats since they have fewer to no lice treatments. It is important to note that the assumptions for vessel use are rough estimations, and that there is still uncertainty as to what the actual need of service vessels will be in the future. Consequently, a sensitivity analysis of the vessel use for all technologies is performed by increasing and decreasing the total use of all vessels by 5, 10, and 15%.

Table 3: Assumed need of vessels in kWh/kg for production systems where "X" denotes that the vessel type is used, and "–" means that the vessel is not used for the respective production technology. The table is based on Nistad (2021) and industry information.

Vessel	Smaller working vessels	Larger working vessels	Service vessels < 15 m	Service vessels >15 m	Well boat
Traditional	X	X	X	x	X
(Semi-)Closed at sea	X	X	x Assumed 50% less use than traditional	x	x Assumed 50% less use than traditional
Offshore	-	-	-	x Assumed 50% more use than traditional	x Assumed 50% more use than traditional
Land-based	-	-	-	-	X Assumed 50% less than traditional
Submerged	X	X	X	x	X Assumed 25% less than traditional

For the modelling of the combustion of diesel used in vessels, a generic global process is used (see Appendix 2), and in addition a conversion factor of 82.5 MJ per kg (as provided in the Ecoinvent database) is applied to the required quantities for each technology.

2.7 Emissions to ocean

Emissions from aquaculture facilities include sludge, carbon dioxide from respiration, chemicals, and emissions from copper or other antifouling agents from nets.

Sludge consists of feed loss and feces, which contains nutrients, organic matter, and heavy metals. Sludge collection represents a reduction of emitted particulate matter composed of carbon, nitrogen, phosphorus, and other substances.

In traditional open net farms, sludge is emitted directly into the water. However, land-based and closed technologies have, dependent of the concept, sludge collection on-site. Land-based technologies must collect sludge, but the rate and criteria of removal vary between different facilities and municipalities in Norway (Lomnes, Senneset, and Tevasvold 2019). The cleansing rate is also different between flow through systems and RAS. The minimum legal requirements are 50% removal of suspended matter and 20% removal of biochemical oxygen consumption (BOF_5) (Lovdata 2007). In this study, it is assumed for the land-based technology a 70% of sludge is collected based on numbers presented in (Lomnes, Senneset, and Tevasvold

2019). Sludge from land-based farms is assumed to be centrifuged on the farm and transported with a dry matter content of 30%. Sludge is emitted with a dry matter content of around 10% (Brod and Øgaard 2023).

A review of different closed and semi-closed systems reported a sludge collection efficiency of 60—70% (SARF 2019). In the proposal of Environmental licenses (Miljøteknologitillatelser) that was sent out in 2021, it was proposed to have a criterion of 60% collection of sludge (Nærings- og fiskeridepartementet 2021). However, these numbers might still be too optimistic based on the current technological level. A closed farm in Norway received an emission permit of collection of 45% of particulate matter as this is the amount that can be collected (Statsforvalteren i Møre og Romsdal 2023). However, the technology can collect as much as 50% of particulate emissions (based on information provided by industry). Therefore, in this study it is assumed that 50% of sludge is collected for the closed technology. Sludge for the closed technology is assumed to be transported by boat and then trucked to a sludge treatment facility.

Sludge collection can also be done on-site in the case of submerged and semi-closed technologies, but this is not currently standard practice and thus is not included in our analysis for these cases.

Emissions from smolt production (both regular and post-smolt) are assumed to be emitted into the ocean, since these facilities often are in proximity to the ocean and the same facilities are used both for smolt and post-smolt production. Dissolved nutrients are assumed to not be collected in any of the technologies.

Emissions of organic and inorganic nutrients and carbon are based on a mass balance model by Wang et al. (2012). This model estimates nutrient discharges based on feed composition, feed loss and assimilation rate of salmon. Identical feed composition is assumed for all production systems. In addition, salmon has the same assimilation and retention rate independent of the production system. Therefore, the feed conversion ratio, feed loss and sludge collection are the only drivers that will determine the differences in the amount of emissions in our study. However, feed composition as well as assimilation and retention of nutrients also play a major role in the amount of nutrient discharge. Broch & Ellingsen (2020) calculated the nutrient and carbon emissions of Norwegian aquaculture, and the parameters on assimilation and retention are based on averages from their review presented in Table 4.

Table 4: Assimilation and retention rates of nutrients and carbon in salmon. The values are based on averages from Broch & Ellingsen (2020).

	Rate (assimilated or retained based on amount eaten)
Assimilation P $(E_{A,P})$	37.5 %
Assimilation N $(E_{A,N})$	87.0 %
Assimilation C $(E_{A,C})$	82.0 %
Retention P $(E_{G,P})$	23.5 %
Retention N $(E_{G,N})$	46.0 %
Retention C$(E_{G,C})$	44.5%

In this work an average of 15% for the solubility (S_X) of particulate carbon, nitrogen and phosphorus is assumed, based on the range from literature, which is 10-20% (Broch and Ellingsen 2020). The content on phosphorus and nitrogen in the feed is based on the average feed composition from four major feed producers in 2020 as analyzed by Aas et al. (2022), and carbon in feed is an average presented in Broch & Ellingsen (2020). These values are presented in Table 5.

Table 5: Content of phosphorus, nitrogen, and carbon in feed.

Component	Content in feed (% of mass)	Source
Phosphorus (F_P)	0.94 %	Aas et al. (2022)
Nitrogen (F_N)	5.69 %*	Aas et al. (2022)
Carbon (F_C)	53.5%	Average from Broch & Ellingsen (2020)

*Calculated using Protein= N×6.5

Feed ($eFCR$) is provided by industry as eFCR for the different production technologies, and feed loss (F_W) is provided for some of the production technologies. The amount of F_W varies between different producers, concepts, and technologies and is more uncertain than eFCR. For some of the technologies, primary data from industry partners were received on F_W. For cases where information was not available from the project partners, an estimate of 10% F_W has been used, based on estimates from the literature. This is the maximum value used by Broch & Ellingsen (2020) in their report, but indications from the industry suggest F_W can be as much as 15%.

The emissions are separated into particulate organic emissions (PO_X), dissolved organic (DO_x) and dissolved inorganic (DI_X). The x represent carbon (C), nitrogen (N) or phosphorus (P). DI_C represent respirated carbon dioxide (CO₂). These emissions of are calculated with equations 3-5, that are based on Broch & Ellingsen (2020). The results of this mass balance model give the total amount of nutrient and carbon emissions per kg of produced salmon.

$$\boldsymbol{PO_X = eFCR \times F_X(F_W + (1 - F_W)(1 - E_{A,X}))(1 - S_X)} \tag{3}$$

$$\boldsymbol{DO_X = eFCR \times F_X(F_W + (1 - F_W)(1 - E_{A,X}))S_X} \tag{4}$$

$$\boldsymbol{DI_X = eFCR \times F_X(1 - F_W)(E_{A,X} - E_{G,X})} \tag{5}$$

The amount of sludge is estimated based on Aas (2021) which reported for a smolt facility with RAS that per kg feed, 10% is feed loss, and of the feed amount eaten, 25% is feces. Therefore, per kg of feed given, the sludge is the sum of feed loss and 25% of eaten feed. This sludge has a dry matter (DM) of 85%. Equation 6 is used to calculated sludge amount per kg salmon produced based on $eFCR$ and F_W.

$$\boldsymbol{kg\ sludge\ (85\%\ DM)/kg\ salmon = F_W \times eFCR + (1 - F_W) \times eFCR \times 0.25} \tag{6}$$

Hilmarsen et al. (2018) reports that per kg feed used, there is 1.5-2.0 kg sludge produced with 10% dry matter content. Sludge is emitted with a 10% dry matter, therefore equation 7 is used to convert the mass of sludge with 85% dry matter into sludge with 10% dry matter.

$$kg\ sludge\ (10\%\ DM)/kg\ salmon = \frac{kg\ sludge\ (85\%\ DM)\ /kg\ salmon * 0.85}{0.10}$$
(7)

Two studies have analysed the chemical compositions of sludge from smolt production. Brod and Øgaard (2023) examined sludge from several smolt facilities between 2010 and 2023 while Aas and Åsgård (2019) investigated one smolt facility. Table 6 presents the chemical composition of sludge based on the values reported in these 2 studies. It is assumed that all these components are particulate, and that the values are representative of sludge composition also for grow-out fish.

Table 6: Chemical composition of sludge based on Brod and Øgaard (2023). Molybdenum and Manganese is based on Aas and Åsgård (2019).

Component	Value	Unit
Dry matter	90.9	%
Calcium	0.0473	kg/kg dry matter sludge
Potassium	0.0012	kg/kg dry matter sludge
Magnesium	0.0033	kg/kg dry matter sludge
Svovel	0.0034	kg/kg dry matter sludge
Sodium	0.0031	kg/kg dry matter sludge
Chloride	0.0018	kg/kg dry matter sludge
Iron	0.0007	kg/kg dry matter sludge
Aluminium	0.0004	kg/kg dry matter sludge
Cadmium	0.0000005	kg/kg dry matter sludge
Lead	0.0000008	kg/kg dry matter sludge
Mercury	0.0000001	kg/kg dry matter sludge
Nickel	0.0000049	kg/kg dry matter sludge
Zinc	0.000373	kg/kg dry matter sludge
Copper	0.0000165	kg/kg dry matter sludge
Chrome	0.0000046	kg/kg dry matter sludge
Arsenic	0.0000014	kg/kg dry matter sludge
Molybdenum*	0.00000079	kg/kg wet weight sludge
Manganese *	0.000128	kg/kg wet weight sludge

*These values are based on Aas and Åsgård (2019)

2.8 Use of antifouling agents

The use of copper impregnation has declined over the years, and the use of other biocide active compounds as antifouling agents have increased, such as tralopyril and pyrithione zinc (Miljødirektoratet 2023). In 2021, the use of copper (copper dioxide) was approximately 1100 tons. The same year, the volume of salmon sold was 1 562 415 tons (Fiskeridirektoratet 2023). Thus, on average in Norway, the input of copper dioxide was 0.704 g per kg salmon produced. This value is assumed in the current work for traditional, one semi-closed, and for the submerged technologies.

Copper emissions from nets that are copper impregnated have been estimated using a leaching rate of 7 µg/cm^2/day from Ayer et al. (2016) who estimated the environmental impacts of culturing Atlantic salmon in copper-alloy mesh net-pens using infrastructure and operating data from a pilot study in Chile in 2012. In this study, the associated emissions of copper per kg salmon farmed are only considered for traditional, submerged, and for one of the semi-closed technologies.

Zinc emissions from nets and copper emissions from antifouling paint, although important for the toxicity impacts, are not included in the study, as no data were received from the industry partners and no sources in the scientific literature were found.

2.9 Lice treatment

Based on the information received from the industry, for the traditional system the lice treatment operations were modelled by the usage of hydrogen peroxide. Appendix 2 shows the inventory processes modelled. In the case of offshore systems, based on the inputs from the industrial partners, half of the quantity from the traditional systems was used while all the other cases have no lice treatment. The amounts of hydrogen peroxide modelled as an input to the system are assumed to be emitted into the ocean.

2.10 Oxygen usage

In some technologies such as land-based, closed, and semi-closed technologies, adding supplementary oxygen might be necessary. For the relevant cases, data for oxygen use were received from the industry partners. Since the oxygen was generated on-site for all cases, and this was embedded in the electricity consumption, oxygen has not been included as a separate activity to avoid double counting. The environmental burden of using liquid oxygen can be quite high, depending on the electricity mix used to generate oxygen. The salmon may also require supplemental oxygen during lice treatments, but this aspect is not modelled in this study as primary data were not available.

2.11 Infrastructure

Within infrastructure, the material use of plastic, glass fiber, steel, concrete, and other materials are modelled. The total amounts per production unit are converted to kg per kg LW salmon produced. For all production technologies primary data were received for the average biomass annual production which was used for the conversion per functional unit. The lifetime of the infrastructure is assumed to be 20 years, except for some cases where the industry partners delivered other data for their company's case (closed and offshore technologies). For the nets, in the case of the offshore and traditional technologies, the lifetime of the plastic is assumed to be two years based on an internal SINTEF report. The sensitivity to the lifetime of steel has been tested for all the impact categories, by increasing and decreasing the lifetime of steel by 5, 10 and 15%.

2.12 Transport

Three different types of transport activities are within the system boundaries of the technologies assessed in this study: the transport of infrastructure from the production country to Norway, the transport of dried sludge from the aquaculture farms to a generic biogas plant, and the transport of dead fish from the farms to a generic incineration plant.

The transport of infrastructure for the offshore technologies which are produced in China, is assumed to be done by container ship via sea from Shanghai, China to Oslo, Norway for both concepts evaluated in this work. For the other technologies, the transport is embedded in the market processes of the materials needed and it is assumed that the production units are assembled in Norway.

The transport of sludge is modelled for only technologies in this study, land-based and closed, and it is assumed to be done by lorry over a distance of 100 km. In the case of land-based technology, sludge is assumed to be first dried on the farm and then transported with a 30% DM content while for the closed technology the transported sludge is assumed to have a 10% DM content.

Transport of dead fish is assumed to be done by boat and over 500 km for all the cases. However, these distances are dependent on locality and will vary greatly depending on where the production unit is located.

2.13 Energy

In this work, the energy carrier for all technologies and concepts evaluated is assumed to be 100% electric. However, approximately 55% of traditional aquaculture farms are run with diesel aggregates (Nistad et al. 2021) and most production facilities also have a back-up diesel aggregate. In this study, for a fair comparison, all technologies were modelled using the same energy carrier.

In the main assessment for this study, the average Norwegian electricity mix has been assumed. However, an electricity scenario was modelled in addition for all technologies and concepts where the average EU electricity mix was used. A sensitivity analysis for electricity demand has been done, using the Norwegian electricity mix for production of grow-out fish for all technologies, increasing and decreasing the electricity consumption by 5, 10 and 15%. Further work in the project will explore different energy carriers for the production technologies in the scenario assessments.

For modelling the energy needed to dry the sludge across all cases, it is assumed that 0.502 kWh are used per kg wet sludge, based on a heat of vaporization of water of 2260 Joule per g (Datt 2011). Nevertheless, depending on each production facility’s routines, the energy requirements for drying up the sludge might vary, as heat of vaporization is not constant, and it depends on water temperature. Thus, the initial temperature of the collected sludge is an important factor for determining the exact requirements of energy.

2.14 Treatment of effluents

For the storage of dead fish, the usage of formic acid is modelled, and the same input across all technologies, at 27 g per kg dead fish as indicated in (Johansen et al. 2022), is assumed. Biogas production from sludge as well as the incineration of the dead fish fraction are not modelled in the main analysis, but the transport of these fractions of biomass to the facilities for energy recovery are accounted for within the inventories.

Energy production from the dead fish and sludge have been excluded from the main analysis due to lack of primary data. However, to test the magnitude of the potential environmental benefits from such waste-to-energy conversions, a simple analysis was carried where the dead fish fraction is incinerated for heat production and the collected sludge is sent to anaerobic digestion. The amounts of dead fish are based on the mortality rate provided by each industry partner, and the amount of sludge is calculated based on equation 6.

3 Findings and discussion

3.1 Overview of results

The results in this section are presented as a comparison of the 8 production technologies and concepts for each of the different impact categories considered in this study. Sections 3.2 to 3.8 include the total footprint for each technology and concept per impact category in addition to the contribution analysis which highlights the hotspot activities in the production system. Section 3.9 includes a comparison of the impacts based on the Norwegian electricity mix and average European electricity mix.

Figure 5 shows the overview of the relative environmental scores obtained for all production technologies and across all seven impacts considered in this work. Within each impact category, the highest score (100%) denotes the technology with the highest impact across all eight cases evaluated, while the remaining seven scores are presented relative to this maximum one.

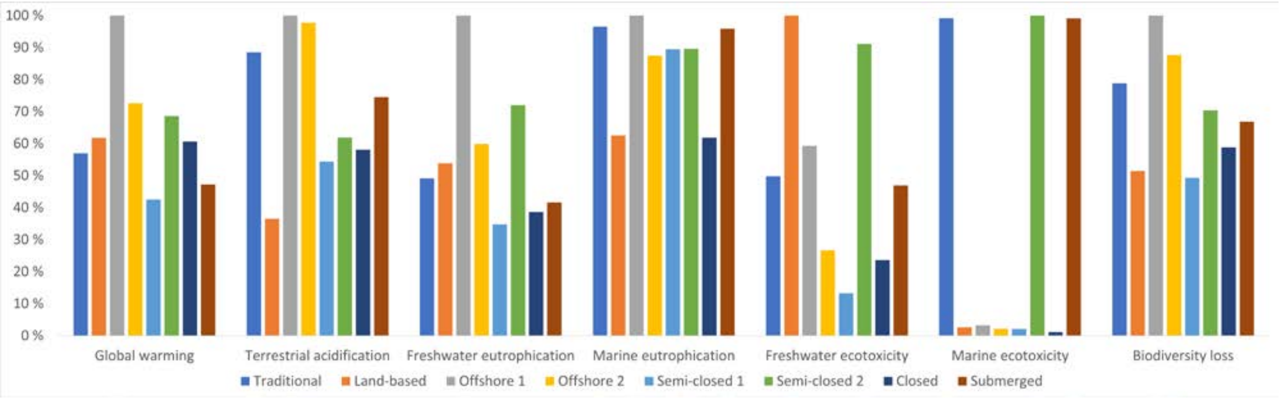

Figure 5: Overview of the relative potential impacts across the different categories for all technologies and study cases considered in the study. For each impact category, the results show the production technology with the highest score among all 8 cases evaluated, which corresponds to the maximum (100%) while the results for the other production technologies are provided in reference to the maximum one. Offshore 1 and offshore 2 show the results for two different types of concepts within the offshore technology and likewise for semi-closed 1 and semi-closed 2.

The environmental performance of the technologies varies to a large degree based on the impact category. Overall, the offshore production concept modelled with case 1 has the highest environmental impacts on GWP, TAP, FEP, MEP and biodiversity loss whereas semi-closed case 1 has the lowest impacts on GWP, FEP, FExP, and biodiversity loss. Traditional technology scores on GWP, FEP and FExP are around the averages of the ranges estimated here while the impacts on MEP and MExP are among the highest. For MEP, the smallest scores correspond to land-based and closed systems. In the case of FExP, land-based and semi-closed case 2 are the technologies with the highest environmental scores while for MExP, traditional, semi-closed 1 and submerged have the highest impacts.

The results highlight large variation in marine ecotoxicology impacts among the technologies and concepts. To be able to understand which underlying factors contribute to the negative impacts and to which degree, a contribution analysis for each impact category is presented further in section 3.2 to 3.8.

3.2 Climate change impacts

Table 7 presents the estimated impacts on climate change using the GWP100 metric: between 390 and 917 g CO_2-eq. per kg salmon at the farm gate. Figure 6 shows the contribution of the processes in the value chain to the GWP100 and highlights the hotspots.

Offshore case 1 has the highest score with 917 g CO_2-eq. per kg salmon at the farm gate. The diesel consumption and combustion in service vessels and well boats are the main drivers in this case, accounting for 486 g CO_2-eq. per kg salmon, which translates to 53% of the total GWP100. The impacts from steel, represented in Table 7 under the category “other materials” accounted for 30% of the climate change impacts.

Offshore case 2 and semi-closed case 2 have the second and third highest impacts on GWP100. Similar to above, diesel use in service and well boats is the main driver with 79% and 47% of the total impact on climate change, respectively. For the semi-closed technology modelled in case 2, plastic and steel consumption are also important for the GWP100, representing 21% and 19%, respectively.

Land-based, closed, and traditional technologies have similar GWP100 estimates with 567, 556 and 522 g CO_2-eq. per kg salmon at farm gate. Electricity consumption is the activity with the highest impact on climate change in the case of land-based technology, with a 33% share of the footprint while diesel used in service boats and plastic consumption represent 28% and 21% respectively of the total GWP100. For traditional technology, most of the environmental burden on climate change (93%), is due to the diesel use in service and well-boats. The activities with the highest contributions on the GWP100 in the case of closed technology are diesel use in boats (53%), plastic consumption (34%) and transport of infrastructure (10%).

Submerged and semi-closed case 1 have the lowest footprints, 433 and 390 g CO_2-eq. per kg salmon at farm gate with diesel used in service and well-boats responsible for 94% and 76% respectively of the total GWP100. In the case of semi-closed case 1, plastic requirements is also an important factor in the climate change footprint, representing 12% of it.

Table 7: **Contribution analysis results for the global warming potential across the technologies presented in units of g CO_2-eq. per kg salmon at farm gate.**

	Total	Diesel Boats	Chemicals and veterinary treatment	Smolt Production	Transport	Plastic	Other materials	Energy
Traditional	522	486	11	22	1	0	0	2
Land-based	567	156	1	24	10	116	69	190
Offshore 1	917	486	2	22	28	89	272	18
Offshore 2	666	524	5	55	13	7	60	3
Semi-closed 1	390	295	1	17	0	49	26	2
Semi-closed 2	629	295	9	18	2	133	120	53
Closed	556	295	1	16	55	189	2	0
Submerged	433	408	7	16	1	0	0	1

Overall, for all technologies except land-based, the most important contributor to GWP100 is the diesel consumption and combustion in well-boats, work boats and service vessels. Energy (as electricity) consumption is the main driver for land-based technology while diesel use in well boats is the second largest contributor here, accounting for 28% of the impacts on climate change. However, some land-based production facilities might not use well boats at all, then this process would be replaced by increased transport by road. Plastic consumption is also an important driver, accounting for the second largest impacts for closed and semi-closed case 1 with 34% and 12% respectively of the GWP100.

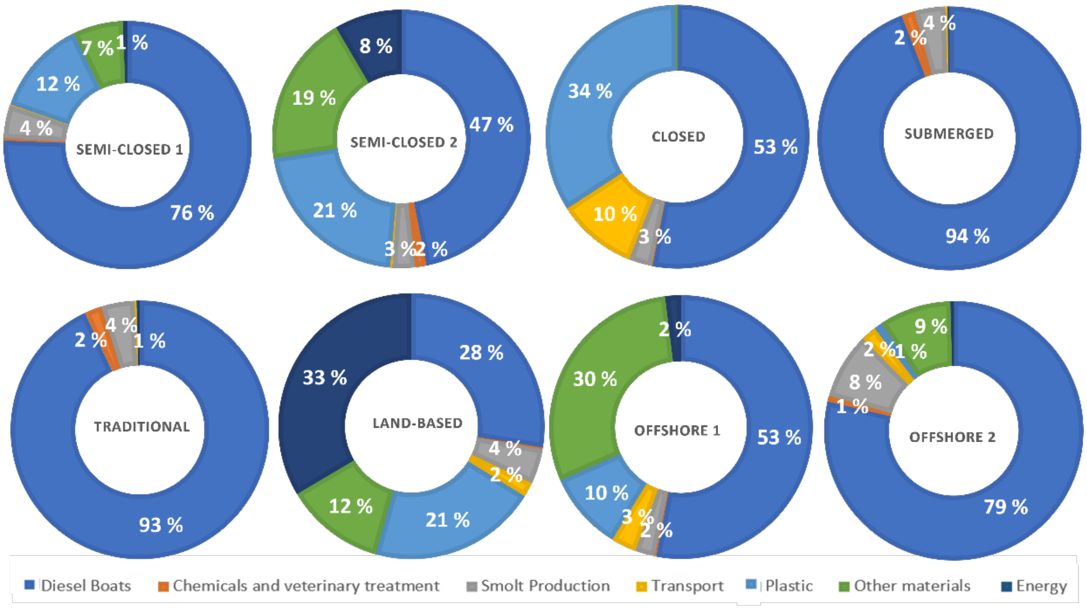

Figure 6: Contribution to global warming potential of the different processes across the technologies and cases and with a breakdown on the 7 main aggregated processes.

In this analysis, it is assumed that all technologies operate on a 100% Norwegian electricity mix. However, it is important to keep in mind that currently many aquaculture facilities may not be electrified, and if the energy carrier for the operations is diesel or at high peak the source of the electricity is of European and not Norwegian origin, the climate change impacts would be higher. To test the sensitivity of the results estimated here to the electricity mix, section 3.9 presents the GWP100 scores for all technologies and concepts when the Norwegian electricity mix is replaced by the European one. In addition, further sensitivity analysis is performed for vessel use, electricity consumption, and lifetime of steel, see section 3.10.

Based on the results presented here, producing 1 kg of salmon at the farm gate with the semi-closed concept modelled in case 1 (which has the lowest GWP100 score) represents 43% of the environmental burden on climate change impacts of the production with offshore technology modelled in case 1 (the highest GWP100 score).

Previously published results on climate change impacts from Norwegian salmon aquaculture from Johansen et al. (2022) reported a carbon footprint of 3800 g CO_2-eq. per kg LW salmon at the farm gate when produced with traditional technology. Of this, 75% is due to feed for grow-out fish production, and 800 g CO_2 eq. per kg LW salmon at the farm gate due to impacts from land use changes. When excluding feed, the carbon footprint is 950 g CO_2-eq. per kg LW salmon. The GWP100 for traditional technology in this study is estimated at 522 g CO_2-eq. per kg salmon at farm gate (shown in Table 7), thus 45% lower than in Johansen et al. (2022). The differences in results are mainly because feed impacts from smolt production are excluded in this study and in addition, in Johansen et al. (2022), it has been taken into account that around 55% of the traditional aquaculture farms are run on diesel aggregates. In this study, traditional technology has been assessed with 100% electricity as energy carrier on-farm.

The relative order of GWP100 results among the production technologies is different in this study than what was reported in the literature review by Philis et al. (2019) where land-based had the highest impacts on climate change. Nevertheless, Philis et al. (2019) evaluated only 3 different production technologies (closed sea-based, land-based, and traditional) thus offshore was not included in their ranking. In our analysis, semi-closed case 2 has the third highest score while semi-closed case 1 has the lowest one, which shows that even within the same production technology there may be huge variations in GWP100. This is primarily due to differences in infrastructure, as the semi-closed technology modelled in case 2 has more steel and plastic requirements than the production concept modelled in semi-closed case 1. In addition, the latter does not require the addition of oxygen which also leads to lower overall energy consumption. In this study, land-based technology has the fourth highest climate change score; nevertheless, impacts from land use and land use change were not considered.

There can be potential reductions in climate change impacts when the system boundary is extended to include the benefits of waste-to-energy production from the biomass waste flows. This includes the energy and heat generation from dead fish incineration for all technologies and concepts and the benefits from biogas production through anaerobic digestion from sludge collected from land-based and closed technologies. These two potential waste management pathways have been modelled in this study with generic processes from the Ecoinvent database (presented in Appendix 2) due to the limited data available. Thus, these reduction potentials are just a first attempt to highlight the mitigation potential of such waste-to-energy treatments. The reduction potential estimated is in the range of 0.4% - 8% of the initial carbon footprint. However, for all technologies except land-based and closed, the benefits come only from the incineration of dead fish, where a higher benefit is equal to a higher mortality. Reducing the mortality rate would also decrease the impact on climate change by increasing production. If energy production from dead fish incineration and biogas from sludge are included within the system boundary, the climate change impacts would be reduced by 3% for closed and land-based technology.

3.3 Terrestrial acidification

Terrestrial acidification impacts reflect changes in soil acidity due to acid depositions following air emission of NOx, NH_3, and SO_2. The estimated impacts on TAP are presented in Table 8 with results ranging between 4343 and 11980 mg SO_2-eq. per kg salmon at the farm gate. Additionally, the contribution analysis available in Figure 7 highlights for all technologies, the combustion of diesel as the main driver for terrestrial acidification with shares between 75% (in the case of land-based technology) and 97% (for traditional technology) of the total impacts on TAP.

Offshore technology with both cases 1 and 2 has the highest scores, 11890 and 11623 mg SO_2-eq. per kg salmon at farm gate, followed by the traditional technology with 10532 mg SO_2-eq. per functional unit. For offshore case 1, which is the technology with the highest impact, steel use (in Table 8 under the “other materials” category) and transport of infrastructure are the second and third highest contributing processes, contributing 6% and 5% respectively to the impacts on TAP. The second highest contributing process to acidification for offshore case 2 is the transport of infrastructure, which in this case is modelled to be shipped by sea container from Shanghai port in China (assumed as the country of production) to Oslo port, in Norway.

Diesel combustion in vessels is responsible for the largest share of impacts on the environment from this transport activity. Nevertheless, this is not directly related to the operation of the aquaculture facilities, but rather a characteristic of the transport mode for the infrastructure.

Table 8: Contribution analysis results for the terrestrial acidification potential across the technologies presented in units of mg SO_2-eq. per kg salmon at farm gate.

	Total	Diesel Boats	Chemicals and veterinary treatment	Smolt Production	Transport	Plastic	Other materials	Energy
Traditional	10532	10189	260	70	7	0	0	5
Land-based	4343	3275	5	78	21	339	152	474
Offshore 1	11890	10196	7	67	573	266	736	44
Offshore 2	11623	10990	16	177	247	21	165	7
Semi-closed 1	6470	6186	5	54	2	147	70	6
Semi-closed 2	7357	6186	255	58	10	389	328	132
Closed	6909	6186	3	51	124	542	4	0
Submerged	8861	8552	248	53	6	0	0	2

Land-based technology has the lowest impact on TAP with 4343 mg SO_2-eq. per kg salmon at farm gate and electricity consumption (shown in Table 8 under the category energy) as the second highest contributing process with 11%.

Submerged, semi-closed case 2, closed, and semi-closed case 1 have scores in descending order whereas submerged has 8861 mg SO_2-eq. mg SO_2-eq. per kg salmon at farm gate and semi-closed case 1 has 6470 mg SO_2-eq. per kg salmon at farm gate. For closed and both semi-closed concepts, plastic is the second highest contributing process with shares between 2% and 8%.

Consequently, using land-based technology to produce 1 kg of salmon at the farm gate is the most environmentally friendly option in the case of terrestrial acidification impacts as it reduces the burden on TAP by 63% compared to offshore technology modelled in case 1 (which has the highest score).

There is a large variation in the scientific literature regarding TAP impacts of seafood production systems with values ranging from 20 to 70 g SO_2-eq. per kg fish or seafood. The potential reason behind this variation is most probably a combination of the differences in the following factors: production technologies evaluated, countries of production (thus different energy sources and mixes), species of fish, system boundaries, and process definitions. The results estimated in our analysis range between 4.3-11.9 g SO_2-eq. per kg salmon at the farm gate and are lower than the previously reported ones. This is mainly due to the differences in energy sources as well as in system boundaries.

In their study, Bohnes and Laurent (2021) report TAP impacts between 50 and 70 g SO_2-eq. per kg of edible seafood for marine fish production in Singapore. They include, under the marine fish production, four technologies (low technology, high technology, RAS and offshore) and the TAP footprint for the offshore technology is 60 g SO_2-eq. per kg of edible seafood, of which approximately 20 g SO_2-eq. are due to the feed, while the rest are due to the fish production and consumables.

When assessing the environmental performance of sea bream and sea bass production in Mediterranean aquaculture, Kallitsis et al (2020) reported 30 and 29 g SO_2-eq. per kg sea bream and sea bass respectively. The system boundary in their study isdifferent from ours, and they consider the impacts from feed and packaging as well. In their contribution analysis, the rearing stage carries 30% and 40% of the impacts on TAP for the sea bream and sea bass production respectively.

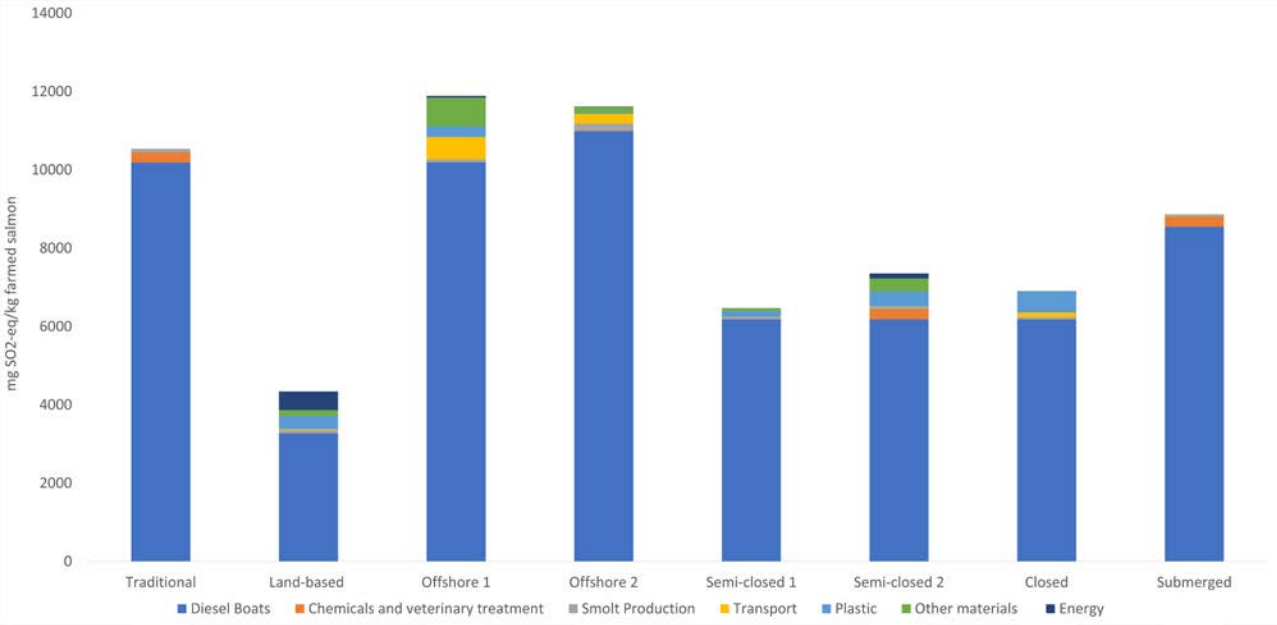

Figure 7: Overview of the impacts on the terrestrial acidification potential across the technologies and cases presented in units of mg SO_2-eq. per kg of salmon at farm gate and with a breakdown on the 9 main aggregated processes.

In a study which investigated the environmental performance of an Italian fish production facility, Zoli et al (2023) report an impact of 24.2 g SO_2-eq. per kg of European sea bass at farm gate and respectively 20.6 g SO_2-eq. per kg of gilthead sea bream. Their system boundary includes additional processes, which makes direct comparison difficult. Nevertheless, they report approximately 5% of the TAP footprint to be due to infrastructure and equipment, approximately 15% from farm management, with the remaining 80% attributed to feed production and supply.

3.4 Freshwater eutrophication

Freshwater eutrophication indicates the enrichment of freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds. The impacts on FEP for all technologies and concepts are presented in Table 9 with results ranging between 107 and 308 mg P-eq. per kg salmon at the farm gate. Figure 8 shows the contribution to the FEP of the processes from the value chain and it highlights the main hotspots for each technology.

Offshore technology modelled in case 1 has the highest impact on FEP, 308 mg P-eq. per kg salmon at the farm gate. The steel production process is in this case the main driver with 46% of the impact on FEP, followed by diesel use in boats, responsible for 35%.

The following 3 highest impacts of FEP are in the semi-closed case 2, offshore case 2, and land-based technology with 222, 184 and 166 mg P-eq. per kg salmon at the farm gate, respectively. In the case of the semi-closed (case 2) technology, the largest share of impacts on FEP is due to diesel use in service vessels, and well and work boats. The largest environmental burden in the case of land-based technology is due to energy consumption (48%), while for the offshore case 2, 64% of the FEP impacts are due to the diesel burned in service and well-boats.

Table 9: Contribution analysis results for the freshwater eutrophication potential across the technologies presented in units of mg P-eq. per kg salmon at farm gate.

	Total	Diesel Boats	Chemicals and veterinary treatment	Smolt Production	Transport	Plastic	Materials	Energy	Nutrient emissions	Smolt emissions
Traditional	151	110	30	10	0	0	0	1	0	0
Land-based	166	35	1	11	2	24	12	81	0	0
Offshore 1	308	110	1	10	4	31	144	8	0	0
Offshore 2	184	118	3	26	2	2	32	1	0	0
Semi-closed 1	107	67	1	8	0	17	14	1	0	0
Semi-closed 2	222	67	29	8	0	32	63	23	0	0
Closed	119	67	0	7	18	26	0	0	0	0
Submerged	128	92	28	8	0	0	0	0	0	0

The semi-closed technology modeled in case 1 has the lowest impact on FEP, 107 mg P-eq. per kg salmon at the farm gate with 62% of this score due to the burning of diesel in service and well-boats, followed by plastic consumption (15%).

Previously reported LCA results on FEP impacts from aquaculture systems range from 1100 to 1900 mg P-eq. per kg of fish (Bergman et al. 2020; Zoli et al. 2023) while the footprints estimated in this study are considerably lower, between 107 and 308 mg P-eq. per kg of salmon at the farm gate. Nevertheless, these previous studies evaluated other fish species in other production countries and moreover used different characterization methodologies and both the system boundaries and the functional units are different than this study. Due to such differences, a direct comparison of results is rather difficult, but in general our total FEP footprints represent between 6% and 28% of the previously reported ones.

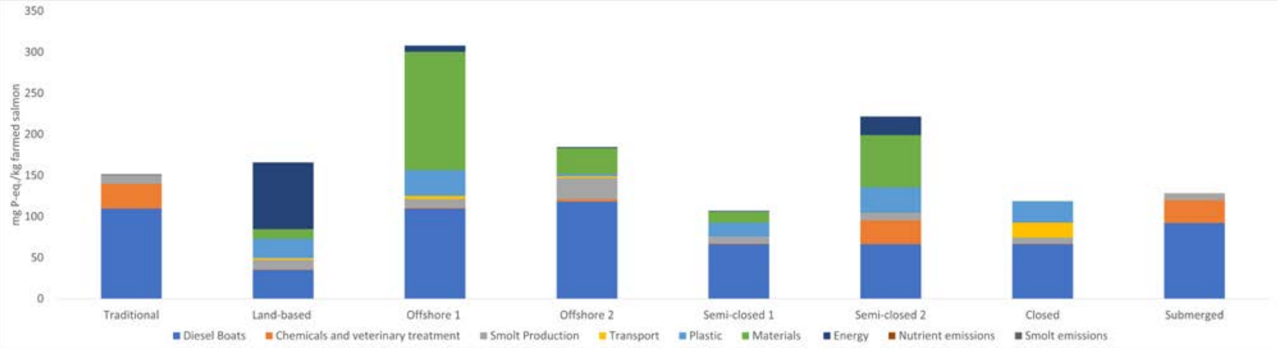

Figure 8: Overview of the impacts on the freshwater eutrophication potential across the technologies and cases presented in units of mg P-eq. per kg salmon at the farm gate and with a breakdown on the nine main aggregated processes.

In their study, Bergman et al (2020), report 1100 and 1900 mg P-eq. per kg of tilapia fillets when economic and mass allocation respectively were considered in their environmental assessment of aquaculture production in Sweden with land-based RAS technology. They report that 20% of these impacts are due to the grow-out phase, while the rest are attributable to feed.

In another study which investigated the environmental performance of an Italian fish production facility, Zoli et al 2023 report an impact of 1400 mg P-eq. per kg of European sea bass at the farm gate and respectively 1200 mg P-eq. per kg of gilthead sea bream. Their system boundary includes additional processes, which makes direct comparison difficult. Nevertheless, they report approximately 10% of the FEP footprint to be attributable to infrastructure and equipment, which is in line with our findings.

3.5 Marine eutrophication

Marine eutrophication impacts indicate the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds. Figure 9 shows the results estimated for the impacts on MEP due to the production of 1 kg of salmon at the farm gate using the different technologies.

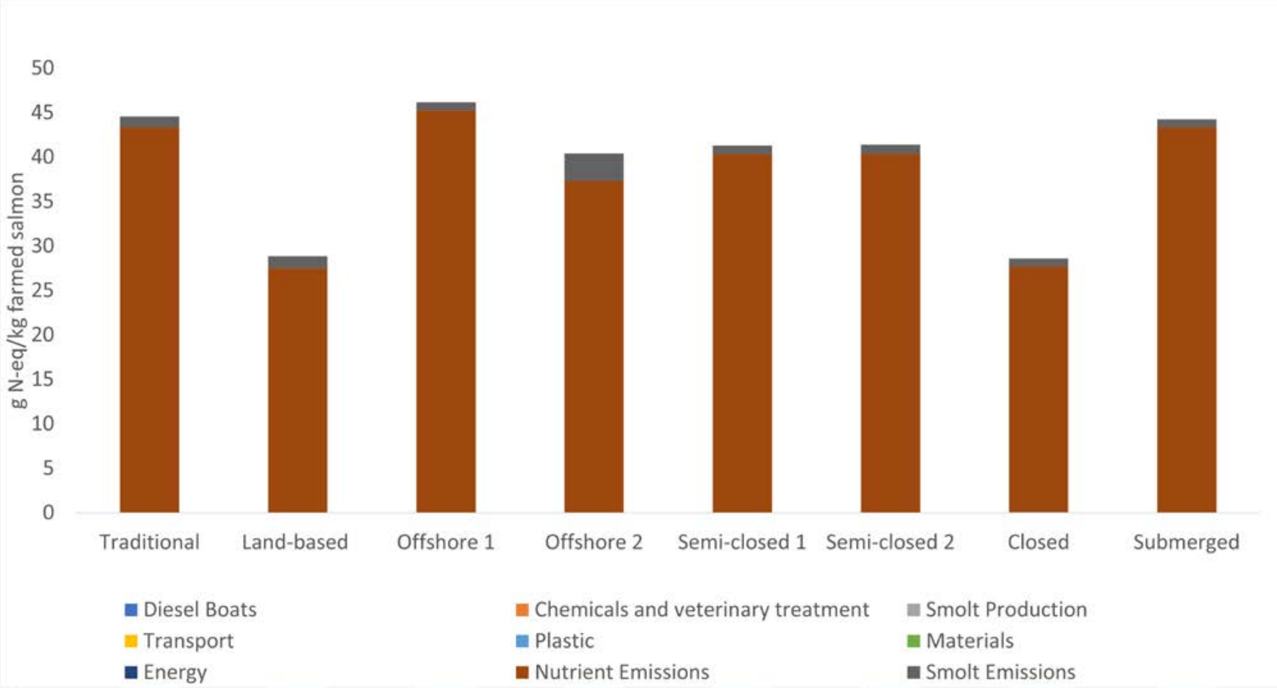

Figure 9: Overview of the impacts on the marine eutrophication potential across the technologies and cases presented in units of gr N-eq. per kg salmon at farm gate and with a breakdown on the nine main aggregated processes.

The offshore (case 1), traditional, and submerged technologies have the highest estimated impacts on MEP, with footprints of 46, 45 and 44 g N-eq. per kg salmon at the farm gate respectively. The nutrient emissions to the ocean from the grow-out phase are the dominant contributors to this impact with shares between 92% and 98%. These are nitrogen emissions from sludge, which includes both feed loss and feces. The nitrogen emissions from the smolt production phase are responsible for the rest of the impacts on MEP.

The following 3 highest MEP impacts estimated in our study here are for the semi-closed (case 1 and 2) with 41 g N-eq. per kg salmon at farm gate each, and offshore case 2 with a corresponding footprint of 40 g N-eq. per kg salmon at farm gate respectively. The share of impacts due to the nutrient emissions to the ocean from the grow-out phase is 98% in the case of both the semi-closed concepts and 92% for the offshore case 2.

The closed and land-based technologies have the lowest impacts on MEP each with an estimated footprint of 29 g N-eq. per kg salmon at the farm gate and 97% and 95% respectively due to the nutrient emissions to the ocean from the grow-out phase. This is because these technologies collect sludge and therefore reduce the amounts of nutrient emissions leading to marine eutrophication.

When investigating the environmental performance of an Italian fish production facility, Zoli et al (2023) report an impact of 141 g N-eq. per kg of European sea bass at farm gate and 113 g N-eq. per kg of gilthead sea bream at farm gate respectively. Their system boundary includes additional processes, which makes direct comparison difficult, but overall our estimated results here represent between 20% and 40% of the results from Zoli et al (2023).

3.6 Freshwater ecotoxicity

Freshwater ecotoxicity indicates the potential impact on freshwater organisms due to toxic substances emitted to the environment. Table 10 presents the contribution analysis for FExP across the technologies evaluated. The land-based technology has the highest impact on freshwater ecotoxicity with an estimated 52 g 1.4DCB-eq. per kg salmon at farm gate. The main contributor to this impact is the electricity consumption process, which accounted for 87% of the total emissions. The lowest score for the impacts on FExP is from production of 1 kg of salmon at the farm gate with the semi-closed technology modelled in case 1 (7 g 1.4DCB-eq.).

Table 10: Contribution analysis results for the freshwater ecotoxicity potential across the technologies presented in units of g 1.4DCB-eq. per kg salmon at farmed gate.

	Total	Diesel Boats	Chemicals and veterinary treatment	Smolt Production	Transport	Plastic	Materials	Energy	Nutrient emissions	Smolt emissions
Traditional	26	1	21	3	0	0	0	0	0	0
Land-based	52	0	0	3	0	2	1	45	0	0
Offshore 1	31	1	0	4	0	3	19	4	0	0
Offshore 2	14	1	0	7	0	0	4	1	0	0
Semi-closed 1	7	1	0	2	0	2	2	1	0	0
Semi-closed 2	47	1	21	2	0	2	8	13	0	0
Closed	12	1	0	2	8	1	0	0	0	0
Submerged	24	1	21	2	0	0	0	0	0	0

Figure 10 shows the contribution analysis for the impacts on FExP across all technologies. For the traditional, semi-closed case 1 and submerged technologies, the highest contribution to the FExP impacts stems from the copper wire usage as anti-fouling agent in the nets. Steel consumption included in the materials is the main driver of impacts in the case of offshore case 1 technology, with 61% of the total footprint while in the offshore case 2, semi-closed case 1 and semi-closed case 2 is responsible for 28%, 28% and 17% of the total footprint. In the cases of offshore case 2, the largest impacts on FExP are due to the smolt production process, namely from electricity consumption for the large smolt production phase with shares of 50% of the total footprint.

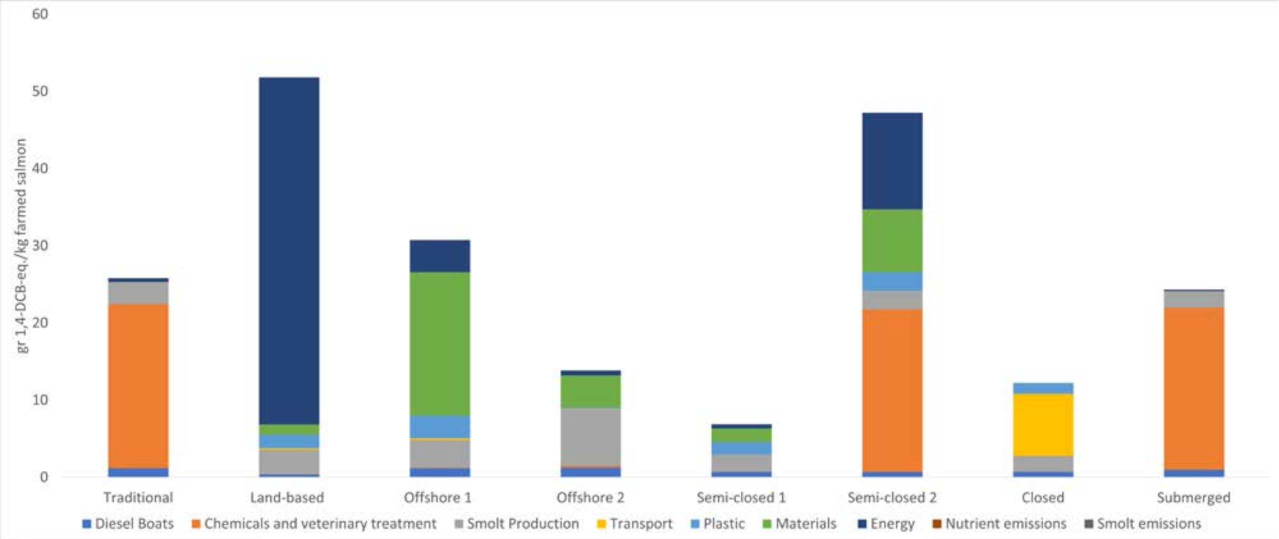

Figure 10: Overview of the impacts on the freshwater ecotoxicity potential across the technologies and cases presented in units of g 1.4DCB-eq. per kg salmon at farm gate and with a breakdown on the nine main aggregated processes.

Zoli et al. (2023) report an average FExP impact of 63 g 1.4DCB-eq. per kg of fish at farm gate for the Italian production of European sea bass and gilthead sea bream with roughly 10% due to the infrastructure and equipment, while feed production and supply is responsible for 85% of the footprint. The results estimated in this study and presented in Table 10 are between 7 and 52 g 1.4DCB-eq. per kg salmon at farm gate and are comparable with the ones reported by Zoli et al. (2023).

3.7 Marine ecotoxicity

Marine ecotoxicity indicates the potential impact on marine organisms due to toxic substances emitted to the environment. Figure 11 presents the impacts on MExP and highlights the large variations among the results from the different technologies. The three production technologies with the highest impact are semi-closed modelled in case 2, submerged, and traditional. The impacts of the other four technologies on marine ecotoxicity are substantially lower.

The highest impacts on MExP are from the semi-closed technology modelled in case 2, 2.94 kg 1.4DCB-eq. per kg salmon at the farm gate while the estimated impact for traditional and submerged technologies were 2.92 kg 1.4DCB-eq. and 2.91 kg 1.4DCB-eq. per kg salmon at farm gate respectively. Emissions of copper from nets are the main contributors to these impacts.

Appendix 3 presents the breakdown on the 9 main activities for impacts on MExP only for the land-based, both offshore cases, semi-closed case 1 and closed technologies for a better visualization of the different share of impacts of these activities within the total footprint. These technologies registered much smaller impacts on MExP. Closed technology has the lowest impact across all technologies with an estimate of 0.03 kg 1.4DCB-eq. per kg salmon at the farm gate, and emissions of nutrients from sludge are representing half of this amount, while transport activities are responsible for 30% of the MExP footprint.

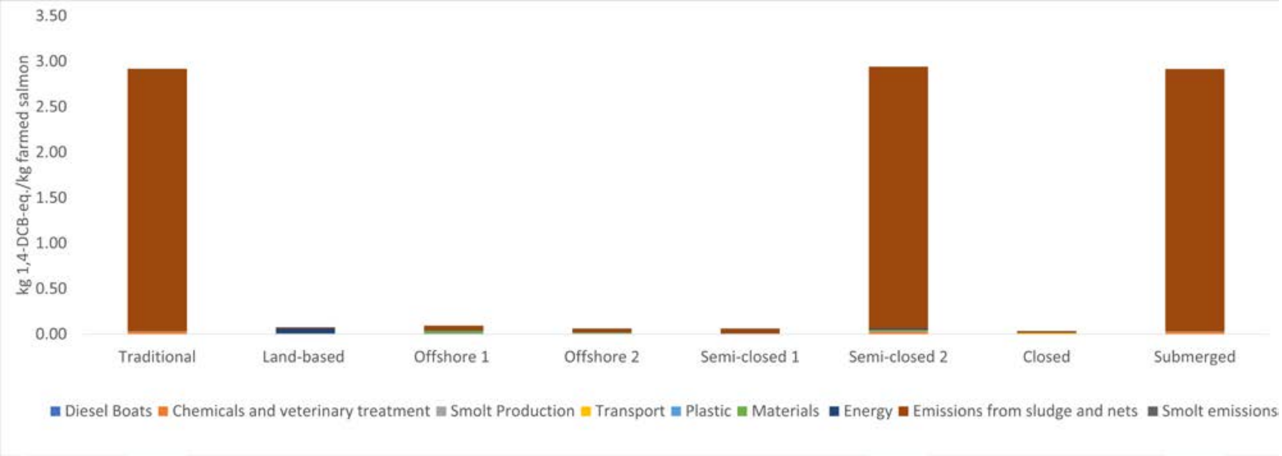

Figure 11: Overview of the impacts on the marine ecotoxicity potential across the technologies and cases presented in units of kg 1.4DCB-eq. per kg salmon at farm gate and with a breakdown on the nine main aggregated processes. An overview only for the land-based, offshore 1, offshore 2, semi-closed 1 and closed technologies is presented in Appendix 3.

The contribution analysis for the MExP in Figure 11 highlights the large variation in results among the technologies and cases. The lowest MExP score which is estimated for the closed technology represents 1% of the highest one which corresponds to the semi-closed technology modeled in case 2. The main driver behind these impacts are the emissions of copper from nets which are modelled for the traditional, submerged and semi-closed (case 2) technologies.

When assessing the environmental performance of sea bream and sea bass production in Mediterranean aquaculture, Kallitsis et al (2020) report considerably higher impacts on MExP, 6150 and 5730 kg 1.4DCB-eq. per kg sea bream and sea bass respectively. Their system boundary includes feed and packaging, and this can partially explain the large differences in the results, in addition to the different geographical boundaries (their study is reflecting the Greek market) and different assessment method (CML in their study). Nevertheless, they report that the rearing stage (growing fish from 2 g to 600 g) contributes approximately 50% of the total footprint on MExP in the case of sea bream, and 60% respectively for the sea bass, which is much higher than our findings.

On the other hand, Zoli et al (2023) report an impact on MExP of 95 g 1.4 DCB-eq. per kg of European sea bass at the farm gate and respectively 79 g 1.4 DCB-eq. per kg of gilthead sea bream at the farm gate when production is localized in Italy. Their study uses a “cradle to gate” approach and considers processes such as the juveniles supply, feed production and supply (e.g., agricultural processes for plant-based ingredient, wild fisheries for marine based protein, and transport), as well as farm management (feed distribution, fish monitoring, and harvest). Zoli et al (2023) report that infrastructure and equipment are carrying 10% of the impacts on MExP, while roughly 85% of the impacts are due to the feed production and supply. Their results are closer to the findings from our report, nevertheless, there are many differences in the system boundaries and process definition between the studies.

3.8 Ecosystem quality – biodiversity loss impacts

Figure 12 presents the impacts on biodiversity loss which in this study are quantified using the ReCiPe endpoint method and are shown in number of species lost (species.yr). The unit species.yr is a measure for the number of unique species, on land and in water that are expected to disappear because of the activities assessed. For example, a 20 species.yr means that 20 species are extinct in 1 year or 2 species in 10 years.

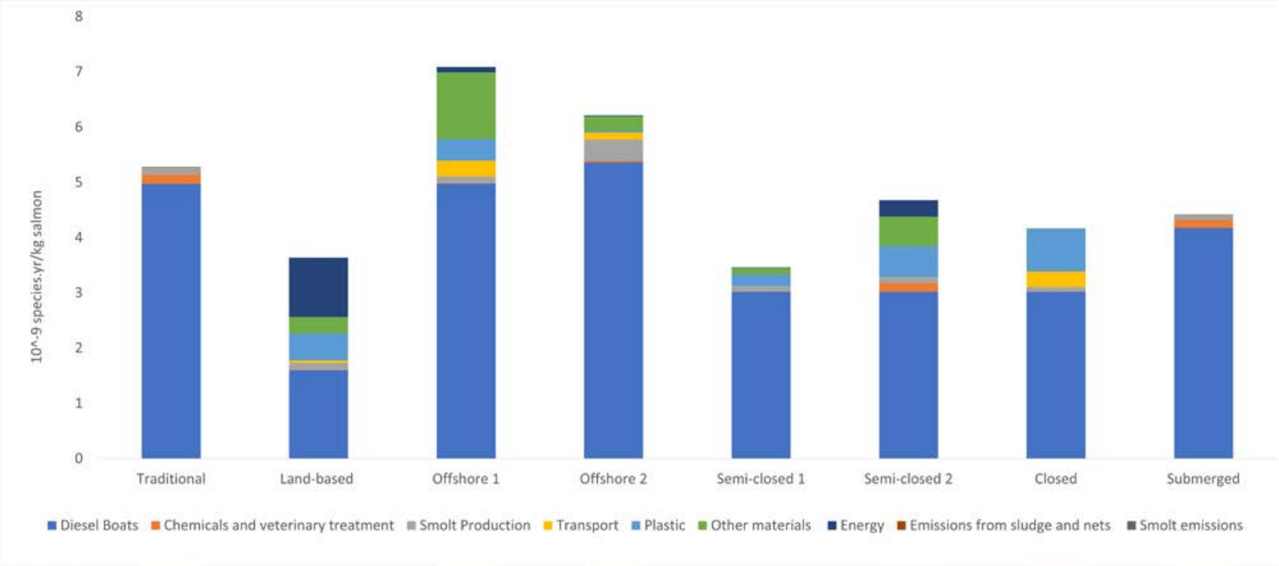

Figure 12: Overview of the impacts on the biodiversity loss across the technologies and cases presented in units of 10^9 species*yr per kg salmon at farm gate and with a breakdown on the nine main aggregated processes.

The highest impacts on biodiversity loss from production of 1 kg of salmon at the farm gate are estimated for the offshore case 1, followed by offshore case 2 and traditional. The semi-closed case 1 and land-based technologies are registering the lowest impacts. In the case of offshore case 1, the technology with the highest impacts, the main contribution to biodiversity loss rises from the diesel consumption for service and well boats (69%) and due to reinforcing steel consumption (17%). Overall, the production and combustion of diesel in service and well-boats is the activity with the highest contribution to the impacts on the biodiversity loss footprint across all technologies, with relative shares between 43% - 88%.

Production and consumption of the different types of plastic (nylon, polyamide, and polyethylene terephthalate) is an important process for biodiversity loss especially for the land-based, semi-closed case 2 and closed technologies. Plastic production and consumption contributed 13%, 11% and 18% towards the total footprint. Steel consumption is also an important activity, responsible for 11% of the total biodiversity footprint in the case of semi-closed case 2 and 17% in offshore case 1. Electricity consumption is, on the other hand, an important activity in the case of land-based technology, accounting for 29% of the total biodiversity footprint.

Among the main 5 drivers of biodiversity loss climate change, land use, and pollution are currently included in the operational life-cycle impact assessment methods, while impacts from invasive species and overexploitation are not yet ready to be used in such assessments. In addition to these 5 main drivers, impacts from water consumption are also incorporated in the biodiversity loss footprints. In the ReCiPe 2016 Endpoint method, impacts from climate change on biodiversity loss are due to the impacts of global warming on terrestrial and freshwater ecosystems. Impacts from climate change on the marine ecosystems are currently lacking in the ReCiPe method.

Figure 13 presents the contribution of each of the twelve impact drivers on biodiversity loss for all technologies. The emissions and resources used in each production technology are translated by the impact assessment method into these drivers, each impacting biodiversity through different mechanisms.

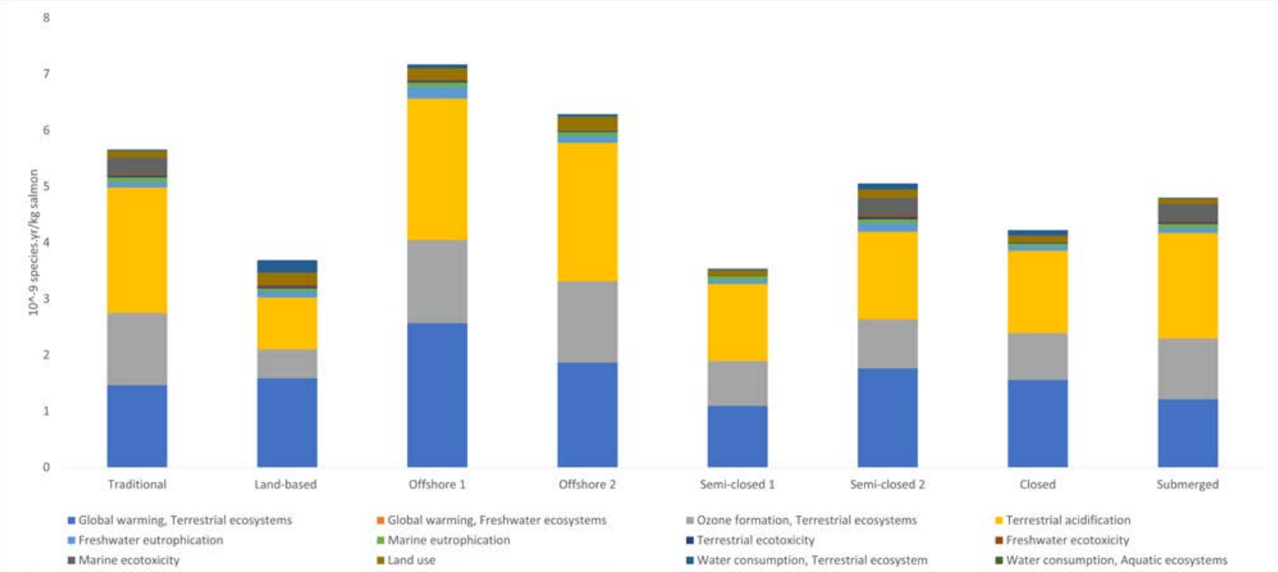

Figure 13: Contribution of each of the twelve impact drivers on the biodiversity loss footprint for each technology presented in units of 10^9 species*yr per kg salmon at farm gate.

Overall, the two main drivers for biodiversity loss in this study are pollution, through terrestrial acidification and climate change through global warming effects on terrestrial ecosystems.

The highest impacts on biodiversity loss in the case of land-based, offshore (case 1), semi-closed (case 2), and closed technologies are registered for the terrestrial species which are affected by the global temperature increase due to the production of 1 kg of salmon at the gate farm. The relative contribution of this driver to the total biodiversity loss footprint ranges from 25% in the case of the submerged technology to 43% for the land-based one.

Terrestrial acidification contributed between 25% to 39% to the total biodiversity loss footprint across all technologies. For traditional, offshore (case 2), semi-closed (case 1) and submerged technologies this is the impact driver with the highest contribution. In the case of terrestrial acidification, impacts on biodiversity loss are due to the loss of plant species following a decrease in soil pH as a consequence of the pollution from changes in acid deposition. Air emission of NOx, NH_3 and SO_2 are driving the changes in acid depositions in terrestrial ecosystems.

Impacts on terrestrial ecosystems due to ozone formation are also important, with contributions to the overall biodiversity loss representing between 14% and 23% of the footprint. In the ReCiPe 2016 impact assessment method (which is the impact method used in this assessment), the impacts from ozone formation on biodiversity are described as the losses in plant species due to increase to ozone exposure.

Land use change is in general the driver responsible for the highest impacts on biodiversity loss. Nevertheless, in this study, having the feed production (for both smolt and grow-out phase) outside the system boundaries, the impacts from land use are in general representing a small share of the overall impacts. For more accurate footprints on biodiversity loss due to salmon production, feed needs to be included in the system boundaries.

3.9 Electricity: Norwegian versus European mix

When replacing the electricity source from the Norwegian electricity mix, with a GWP100 factor of 0.0229 kg CO_2-eq. per kWh (according to the Ecoinvent 3.8 database) with an European electricity mix, with a GWP100 factor of 0.388 kg CO_2-eq. per kWh (same database), the impacts on climate change are increasing for all technologies according to the results presented in Figure 14 (between 30% and 560% increase). In addition to the increase in the overall carbon footprint, the relative order of the technologies changes due to the different requirements of electricity consumption. Thus, the highest impacts on climate change are then registered for land-based technology with a total footprint of 3.76 kg of CO_2-eq. per kg salmon at the farm gate. The consumption of electricity represents (under the EU electricity scenario) 86% of the total impact on GWP100, in comparison with the 34% under the Norwegian electricity mix. The next most important contributing processes under the EU electricity mix are smolt production (5%), diesel consumption and combustion in the service boats (4%) and consumption of plastic (3%).

In the case of the offshore case 1, which in the scenario with Norwegian electricity mix has the highest impact on climate change (shown previously in Figure 5), under the EU electricity mix, it is the third most intensive technology, with 1.41 kg of CO_2-eq. per kg salmon at the farm gate. Approximatively half of this footprint is due to two activities: diesel used in the service boats (35%) and electricity consumption during the grow-out phase (21%).

Electricity consumption during smolt production is the main contributor to CC in the land-based, semi-closed case 2, and closed technologies where this process is responsible for 86%, 56% and 46% of the total carbon footprint respectively. The technology with the lowest environmental footprint under the EU electricity mix is the semi-closed case 1, with a total of 0.54 kg of CO_2-eq. per kg salmon at farm gate, where diesel used in service boats (55%), electricity usage during grow-out phase (24%) and plastic consumption (9%) are the top three contributing processes.

In the case of TAP impacts, the range of results increases from between 4.3 to 11.9 g SO_2-eq. per kg salmon at the farm gate (as shown in Table 8) when the Norwegian electricity mix is used to between 7 and 16.4 g SO_2-eq. per kg salmon at farm gate when the European electricity mix was used. These values are closer to the reported ones in the other scientific articles reviewed (with estimates between 20 and 70 g SO_2-eq. per kg fish or seafood product).

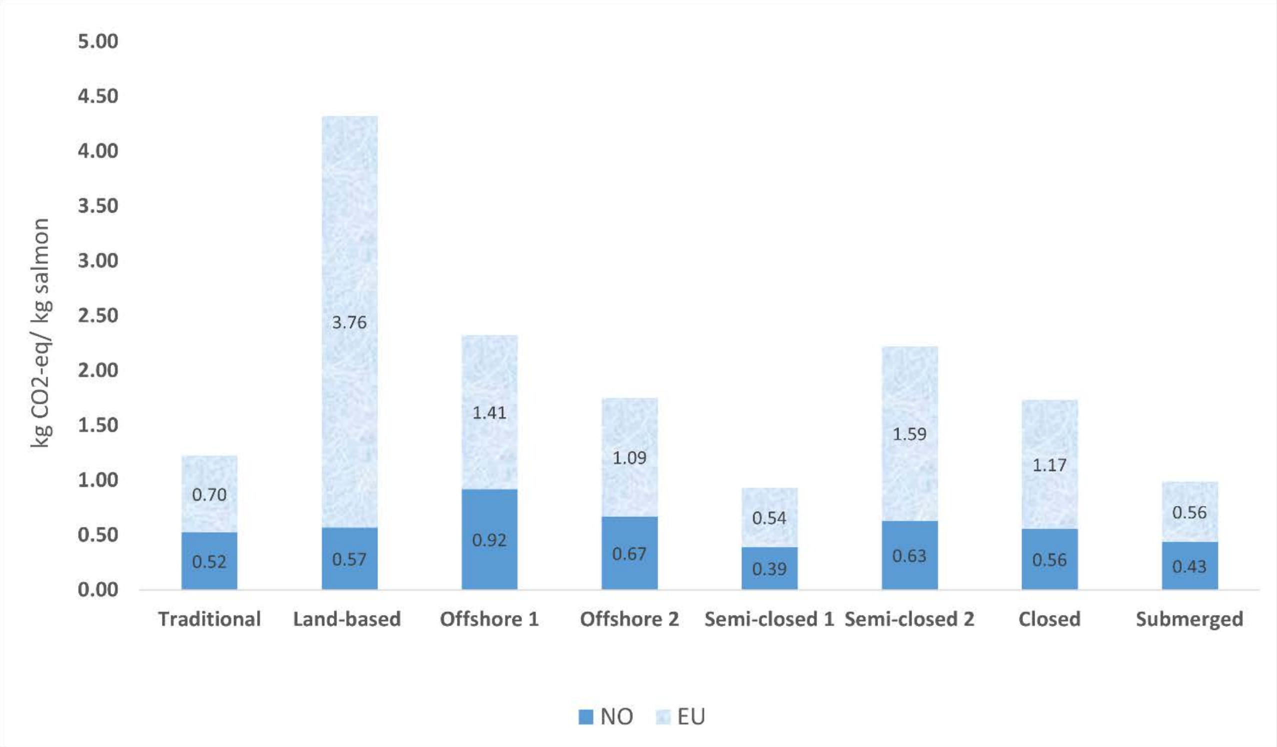

Figure 14: Impacts on climate change for GWP 100 in units of kg CO2-eq per kg salmon at the farm gate with a breakdown by electricity mix: Norwegian (NO; in dark blue) and European (EU; in light blue). Offshore 1 and offshore 2 show the results for two different types of concepts within the offshore technology and likewise for semi-closed 1 and semi-closed 2.

With the change in the electricity source, FEP impacts are increasing as well (between 99% and 2010%). The minimum impact under Norwegian electricity mix is for the semi-close case 1 technology with 107 mg P-eq. per kg salmon at farm gate while the minimum with the continental electricity mix is 2.3 times higher, namely 256 mg P-eq. per kg salmon at farm gate for the submerged technology. The highest impact on freshwater eutrophication when using Norwegian electricity mix is due to the production of salmon with offshore case 1 technology and is estimated at 308 mg P-eq. per kg salmon at farm gate while with the European electricity mix, land-based technology has the highest impact, 3500 mg P-eq. per kg salmon at farm gate.

On the other hand, the range of impacts on MEP is increasing very little when changing the electricity source (between 0.01% and 0.81% increase): from the 28.56 – 46.16 g N-eq. per kg salmon at farm gate with the Norwegian mix, to 28.70 – 46.20 mg P-eq. per kg salmon at farm gate with the European mix.

Freshwater ecotoxicity impacts are increasing as well when the EU electricity mix is used in the models (between 15% and 188%). FExP impacts range between 7 – 52 g 1.4DCB-eq. per kg salmon at the farm gate when Norwegian electricity mix is considered, while with the European electricity mix as energy source, the range is between 11 - 149 g 1.4DCB-eq. per kg salmon at farm gate.

In the case of marine ecotoxicity impacts, the range of results estimated with European electricity is 0.06 – 2.98 g 1.4DCB-eq. per kg salmon at farm gate while the results for the Norwegian electricity are between 0.03 and 2.92 g 1.4DCB-eq. per kg salmon. Thus, the results increase with 0.2% - 174% in the EU electricity scenario.

Impacts on biodiversity loss are larger under the European electricity mix as well, with values between 1.15 and 5.15 times higher than the estimates done for the Norwegian electricity mix. The lowest impacts on biodiversity loss under both electricity options are obtained for the semi-closed technology (case 1), 3.54 * 10^{-9} species*yr per kg salmon at farm gate with the Norwegian mix, a value which increase to 4.25 * 10^{-9} species*yr per kg salmon at the farm gate under the European mix. The highest footprint for biodiversity loss under the European electricity mix is achieved when producing 1 kg of salmon with the land-based technology, 19 * 10^{-9} species*yr, in comparison with 3.7 * 10^{-9} species*yr per kg salmon at farm gate with the Norwegian mix.

The change of the magnitude of impacts on the different impact categories for all technologies and cases assessed (as well as the change in the relative order of the technologies with highest impact) highlight the need for the accurate consideration of the electricity source in aquaculture production systems.

3.10 Sensitivity analysis

The sensitivity analysis was conducted for 3 parameters: vessel use, including both well boats and service vessels (see Figure 15), electricity use during operations (see Figure 16) and lifetime of steel (see Figure 17). The aim of the sensitivity analysis is to see how the total impacts change when the values of these three parameters change. For the sensitivity analysis for vessel use, a total increase and decrease of 5%, 10%, and 15% of vessel use is tested. This change impacts the amount of diesel required and combusted in the vessels. The sensitivity of electricity use tests an increase and decrease of 5%, 10%, and 15% of the on-farm electricity consumption in operations for the grow-out phase. For steel, the lifetime of steel was tested for 5%, 10% and 15% shorter and longer lifetime. These parameters were selected as they are identified as important drivers to several impact categories.

Vessel use, including service and work vessels and well boats are highly uncertain processes since many technologies are in an emerging state and have not yet reached a "normal" operating phase. The vessel use is based on previous estimations and has been updated based on industry information, but the recorded data from industry on this process is lacking for several technologies. In this analysis, only diesel has been used as an energy carrier for vessels, but it could also be important to investigate how impacts may change with the use of electrified or hybrid boats. Increasing or decreasing vessel use has the biggest impacts on global warming potential, terrestrial acidification, and freshwater eutrophication. Both the traditional and submerged technologies can reduce 14% of the total global warming potential with a 15% reduction of vessel use. The least change is seen in the land-based technology that only reduces 4% of the total global warming potential with 15% reduction of vessel use. The sensitivity of terrestrial acidification is quite similar for all technologies with a potential reduction of TAP ranging between 11 and 15%. Impacts on marine eutrophication are the least sensitive to increased or decreased use of vessels, with a maximum reduction of less than 0.004% of the total impacts in this category for the offshore 2 case. Sensitivity of vessel use is linear which means that an increase in vessel use will have the same percentage increase on impact as a reduction in the vessel use has in decreasing the impacts.

As many of the technologies are novel and production is not yet optimized, potentially the electricity consumption per kg live weight salmon may be reduced in the coming years. For all impact categories, the sensitivity of increasing or reducing electricity use was the highest for the land-based technology. This is mostly due to fact that land-based technology has the highest consumption of electricity during the grow-out phase and electricity use is also the main driver of all impact categories for the land-based technology.

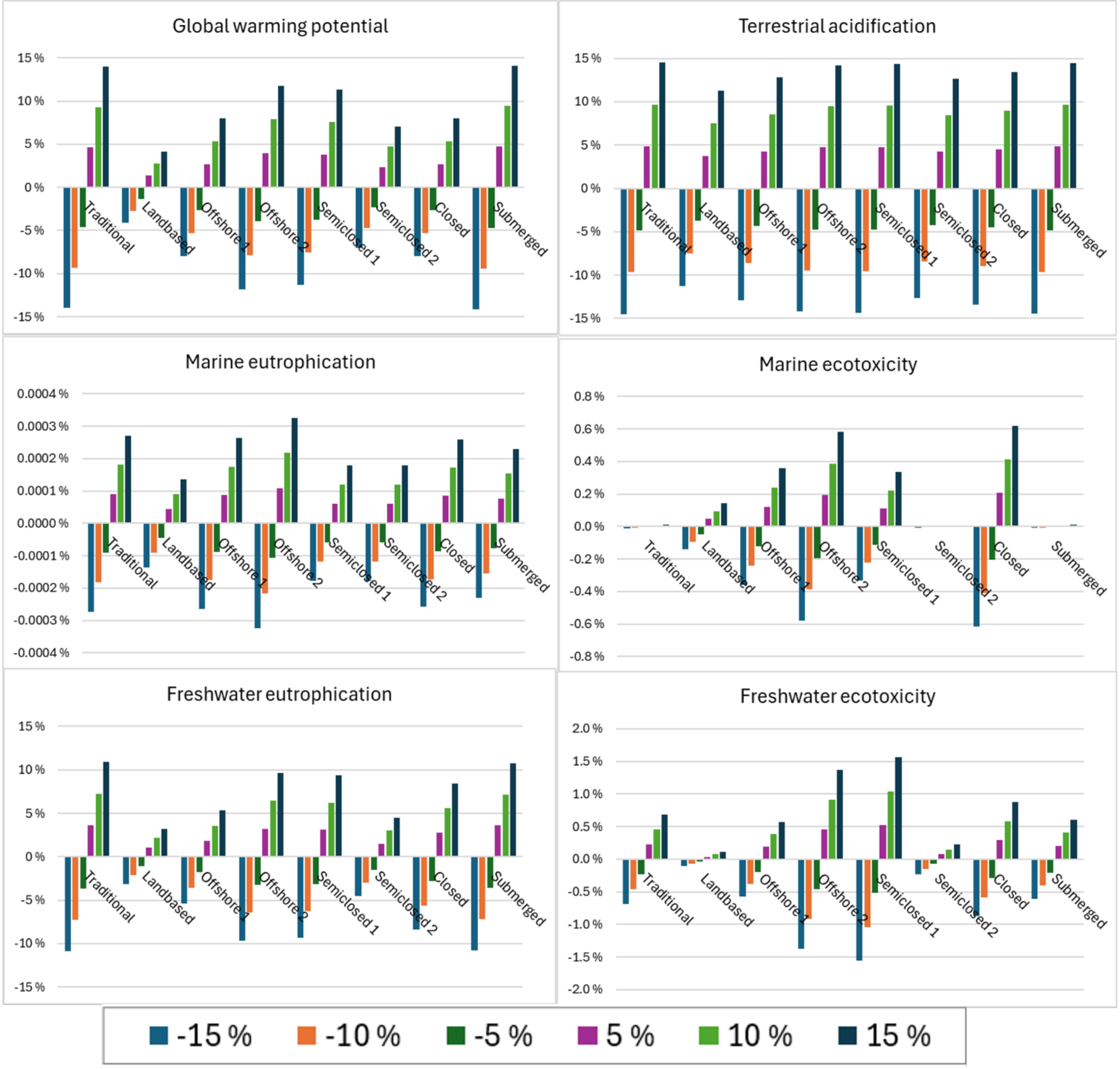

Figure 15: Sensitivity of the total footprint when changing the total vessel use, boat well boats and service vessels with -15%, -10%, -5%, +5%, +10%, and +15%. The changes in total footprint per category are represented as the percentage change to the baseline result which are presented in sections 3.2 -3.7.

The potential reduction was highest for global warming potential, freshwater ecotoxicity, and freshwater eutrophication, were a 15% reduction of electricity used could potentially reduce the respective impacts by 4, 5 and 2% respectively. For semi-closed 2 and closed, electricity is an important driver for freshwater ecotoxicity and therefore, the sensitivity is higher for these technologies as well as for the land-based technology in this impact category. The offshore 1 case had the second highest sensitivity to electricity use for marine ecotoxicity, freshwater ecotoxicity, and marine eutrophication. However, the potential reductions for marine eutrophication are low, below 0.0002 % for offshore 1, and around 0.0005% for the land-based technology.

Figure 16: Sensitivity of the total footprint when changing the electricity use with -15%, -10%, -5%, +5%, +10%, and +15%. The changes in total footprint per category are represented as the percentage change to the baseline result which are presented in sections 3.2 -3.7.

In the sensitivity analysis for the lifetime of steel, the change in the total footprint is largest for offshore case 1, followed by offshore case 2 and semi-closed case 1. These are the technologies that have the highest input of steel in construction. If no other information were given, a lifetime of steel of 20 years was used. A 15% increase refers to 23 years, and a 15% decrease in lifetime refers to 17 years. Increasing the lifetime of steel by 15% could reduce the global warming potential of offshore 1, by around 4%. The biggest change for freshwater ecotoxicity was due to increasing the lifetime of steel by 15% could potentially reduce the impacts of the offshore case 1 by 9%. However, a reduction of the lifetime by 15% would increase GWP by 5% and FExP by 13% for the offshore 1 case. For semi-closed case 2, the lifetime of steel was not available, and a sensitivity analysis was not performed for this case. However, maintenance operations required for steel were not included in this current analysis, and these could potentially increase the total impacts.

Figure 17: Sensitivity of the total footprint when changing the lifetime of steel with -15%, -10%, -5%, +5%, +10%, and +15%. The changes in total footprint per category are represented as the percentage change to the baseline result which are presented in sections 3.2 -3.7.

3.11 Limitations

Different sources of limitations and uncertainties are present in this study, and these should be considered when analyzing the results and drawing conclusions. First, there are the uncertainties regarding novel technologies, especially in the early stages their deployment. These novel technologies have limited available data for inventories, so the results presented here could be affected by the assumptions made during the assessment. For some technologies, there has been only one or two production cycles tested and limited data is available today. Thus, the results produced in this first assessment do not necessarily give an accurate assessment of the environmental performance. There may also be a rapid development in the environmental performance of these technologies as many are not yet fully operational. Therefore, it is expected that with updated values for some of the critical parameters, overall results might change as well, in absolute as well as in relative terms.

Direct emissions of nutrients, organic matter, heavy metals, and chemical leakage are local; the impacts will vary dependent on where they are emitted. In this work, these impacts are only assessed based on global data and therefore there is a limitation as to what the actual local impact would be. There is also a need for more detailed data on the exact levels of direct emissions of sludge and leakage rates. The dominant impacts in the marine ecotoxicity category are copper emissions from nets. These findings highlight the need for close monitoring and data collection at aquaculture sites in the future.

Freshwater inputs for smolt production are not considered in this work but could be of relevance to the impact categories such as water depletion. Similarly, wastewater output from the land-based system is not modeled here as data were not collected, but this could have implications for the results on the marine ecotoxicity as well as marine eutrophication.

Diesel combustion in vessels represents a hotspot activity for multiple impact categories. In this study, this activity has been modelled using a generic process from the Ecoinvent database (shown in Appendix 2), which describes the service of burning 1 MJ of marine diesel in fishing vessels and representing the geographical boundaries of the global market. An improvement of the estimative impacts could be achieved by replacing this global process with the emissions factors provided by Statistics Norway which are more representative for the country (SSB 2017). Statistics Norway provides emissions factors for the following gasses and heavy metals: CO_2, SO_2, lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), CH_4, N_2O, NO_x, non-methane volatile organic compounds (NMVOC), carbon monoxide (CO), particulate matter below 10 um (PM10), particulate matter below 2.5 um and dioxins. When comparing the impacts of the two alternative processes, burning 1 MJ of diesel with the Ecoinvent global process and the Norwegian air emission factors from 1 MJ of marine diesel from mobile combustion sources, the latter represent 87% of the carbon footprint of the former.

A direct comparison with previous results should be made with caution as methodological steps and system boundaries vary both between this study and previous ones. However, comparing our findings is still useful especially to verify or identify either similar or different burden contributions. Findings from previous literature has indicated that land-based technology have higher contributions to several impact categories such as GWP and TAP, due to a higher electricity consumption (N. W. Ayer and Tyedmers 2009; Ghamkhar et al. 2021; Philis et al. 2019). Land-based production in Norway will, in many cases, have a lower carbon footprint than land-based production in other countries if the electricity used is a Norwegian hydro-powered electricity mix. These results have been highlighted in Figure 14.

Contributions to EP were lower for the land-based technology (N. W. Ayer and Tyedmers 2009; Ghamkhar et al. 2021; Philis et al. 2019). This is in line with our findings, and are also apparent for the closed technology with sludge collection. There has not been conducted any LCAs on offshore technology, except for a simplified scenario (included in Johansen et al. 2022), where it was found that producing grow-out fish in offshore technology increased the total carbon footprint by 24%. The results show as well that the offshore 1 case had the highest contributions to global warming, terrestrial acidification, freshwater eutrophication, and marine eutrophication, which was due to the high input of steel in this technology. However, increasing the lifetime of steel infrastructure could reduce GWP, FEP, and FEx. Using recycled steel could also reduce impacts associated with this technology.

Bohnes et al. (2019) identified the most important contributor to all environmental impacts in aquaculture production was feed. Johansen et al. (2022) found that feed production accounts for 75% of the carbon footprint of salmon produced in traditional cages. For this project, feed production as well as feed transportation are not included in the assessment here due to the declared initial system boundaries. Different feed compositions are used in different aquaculture companies, and in some cases between different production technologies. Nevertheless, for a comparison of these results with other relevant scientific articles and the literature on aquaculture, modelling of the feed production is necessary. This additional step will allow a more representative result of the potential impact on impact categories such as marine and freshwater eutrophication as well as land use and biodiversity footprints.

3.12 Further work

The results from this report will be used further in the project in assessing the environmental impact of salmon production in 2050 with different production technologies. These findings will be presented in the project's final report. The final report will consist of a holistic assessment of sustainability in scenarios defined within the project and will also include social, economic, and environmental sustainability. A qualitative assessment of environmental impact categories selected by Slette et al. (2023) which are rather unquantifiable in an LCA framework (e.g., sea lice and lice treatment, fish welfare, and escapees) will be carried out further in the project.

The aim of this work has been to perform a screening LCA to highlight major differences between different production technologies for salmon production. However, for more precise results a complete LCA should be considered.

Vessel use in aquaculture operations is identified as a major contributor to several impact categories, notably GWP and TAP. Through the sensitivity analysis, it was uncovered that if the total vessel use (all working vessels, service vessels, and well boats) per technology was reduced by 15%, the reduction of impacts could be as high as 14% for GWP100 for the traditional and submerged technology and ranging between 11-15% for TAP for all technologies.

Our work presents novelty in the inclusion of impacts of emissions from sludge, but these values are largely based on estimates. More data is needed, such as specific feed and sludge compositions. It was uncovered that many producers have stopped using copper as an antifouling agent but have started using other biocide active compounds, such as tralopyril and pyrithione zinc. The emission of copper from nets is the main driver of marine ecotoxicity impacts, and future work should include the use and leakage of other antifouling agents used for nets and painting.

Feed production and transport were defined as outside of the scope of this work. However, this is a shortcoming as feed for salmon is a major contributor to all impact categories for upstream impacts. The different technologies have a different eFCR and hence the scale of upstream impacts associated with feed will also be an important factor in future assessments to consider. A comprehensive environmental LCA of salmon feed with more indicators than just GWP would provide more insights on the upstream impacts of salmon farming.

In this report, both waste-to-energy options (dead fish to incineration and sludge for biogas production) have been modelled using the generic processes available in the Ecoinvent database. These first results show reduction potentials in the range of 0.4% - 8% of the carbon footprint without the energy recovery processes. This highlights the importance of more accurate consideration and modelling of these two waste treatment options for each production technology. In addition, the dominance of the impacts due to copper emissions from nets on the marine ecotoxicity impact category highlights the need for better primary data collection from the aquaculture sites.

4 Conclusion

This report estimates the environmental impacts of producing 1 kg salmon at the farm gate with six different production technologies: traditional, land-based, closed, semi-closed, submerged and offshore. In the case of offshore and semi-closed technologies, two different concepts for each production technology were evaluated. As the concepts are unique in their design and operation, the results for their environmental performance are variable.

Overall, offshore production technology has the higher environmental impacts whereas one of the semi-closed concepts has lower impacts across the majority of the impact categories. Considering the variation between concepts, the semi-closed concept has relatively high impacts across most impact categories. The performance of traditional and submerged technologies are quite similar, with the submerged technology performing slightly better than the traditional technology in most impact categories, mainly due to a lower energy requirement. Land-based and closed technologies show lower impacts than traditional for marine eutrophication and marine ecotoxicity mainly due to the majority of the sludge being collected instead of being released in the marine environment. The performance of the land-based technology is better when modelled with a Norwegian electricity mix in comparison to when it was modelled with a European energy mix containing a higher share of energy from fossil fuels.

For all technologies, vessels, such as work vessels, service vessels, and well boats were a main driver for several impact categories. Impacts from vessels can be reduced with more efficient use of vessels or shifting to electrified or hybrid boats. Since this analysis was mostly based on assumptions for the current use of vessels, the actual impacts per technology may be higher or lower than what has been calculated in this report.

There can be potential reductions in climate change impacts when the system boundary is extended to also include the benefits of energy produced during the biowaste treatment of sludge and dead fish. The reduction potential is roughly estimated to be in the range of 0.4% - 8% of the initial carbon footprint without the energy recovery processes. However, this estimate needs to be re-estimated if better data is available in the future. The increased benefits from dead fish incineration points to increased mortality, which ultimately is negative for aquaculture producers.

Although the impacts associated with feed production are not included in this study, data on eFCR collected in this study is another indicator for comparing the performance of different technologies. In general, land-based, semi-closed and closed systems have lower mortality and hence a lower eFCR than the traditional technology while offshore technology (on average) does not - as of today - have a significantly improved eFCR compared to the traditional technology.

Due to lack of data availability, some inputs such as oxygen during lice treatment, freshwater consumption, primary data on the fuel use in well boats and service boats for different technologies, and total seabed area affected have not been included. The value chain of salmon produced with these technologies is also different. The semi-closed system today only operates until post-smolt stage, and the input parameters might change if the growth-phase is extended until the harvest stage. Thus, the environmental footprints presented in this work might improve if such parameters were included in the analysis.

In conclusion, as the aim of this work has been to perform a screening LCA, the major differences between different production technologies for salmon production are highlighted. However, for more precise results a more comprehensive assessment including feed-related impacts should be considered. Our work is novel due to the inclusion of impacts of emissions from sludge, for now these values are largely based on low quality estimates and thus more data is needed, such as specific feed and sludge compositions.

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6 Appendix

Appendix 1: Inventory request sent to the industry partners

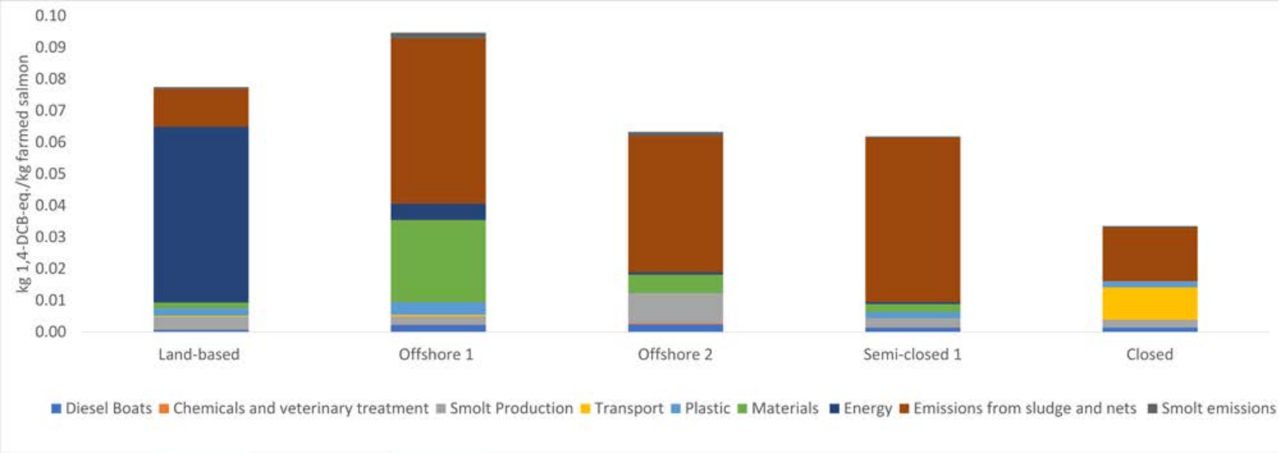
Operation			
Input	**Value**	**Future target Value**	**Importance of the parameter. * indicates lower importance while *** indicates highest importance**
Average smolt size at deployment			**
Average economic feed conversion ratio (eFCR)			***
Average electricity use per kg salmon at harvest			***
Average fuel use /energy use by well boats, service boats at harvest			***
Average oxygen use per kg salmon at harvest			**
Other chemical input per kg salmon at harvest			*
Number of lice treatments per month or per year			**
Mortality %			*
Description of biological waste treatment			*
Feed loss %			***
Annual Biomass Production			***
Equipment			
Total weight of the installation			***
Total amount of plastic per polymer type if available			***
Total amount of steel			***
Total amount of aluminum			***
Maximum biomass capacity			***
Other components like pumps, nets, birds nets, etc.			***
Other materials (e.g., concrete)			**
Description of maintenance services required (cleaning, coating)			***
Expected lifetime in years for whole equipment or individual components			*
Average transport required for the equipment			*
Description of end of treatment, recyclability			*
Production site (country)			***
Amount of seabed area affected between anchor points			*

Appendix 2: Inventory processes from Ecoinvent database per each value chain stage

Value chain stage	Process	*Ecoinvent Process used in the current study*	*Unit*	*Geographical Boundary*
Diesel boats	Diesel in service Boats	*Diesel {Europe without Switzerland}| diesel production, petroleum refinery operation | Cut-off, S*	*kg*	*European*
		Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | Cut-off, S	*MJ*	*Global*
	Diesel in well-boats	*Diesel {Europe without Switzerland}| diesel production, petroleum refinery operation | Cut-off, S*	*kg*	*European*
		Diesel, burned in fishing vessel {GLO}| market for diesel, burned in fishing vessel | Cut-off, S	*MJ*	*Global*
Energy	Electricity	*Electricity, medium voltage {NO}| market for | Cut-off, S*	*kWh*	*Norwegian*
Large and Regular Smolt Production	Electricity	*Electricity, medium voltage {NO}| market for | Cut-off, S*	*kWh*	*Norwegian*
	Lice treatment	*Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, S*	*kg*	*Global*
	Transport of sludge	*Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S*	*tkm*	*European*
	Land use	*Occupation, urban, NO*	*m2a*	*Norwegian*
Chemicals and veterinary treatments	Lice Treatment	*Hydrogen peroxide, without water, in 50% solution state {RER}| market for hydrogen peroxide, without water, in 50% solution state | Cut-off, S*	*kg*	*European*
	Storage of dead fish	*Formic acid {RER}| market for | Cut-off, S*	*kg*	*European*
	Antifouling	*Copper oxide {GLO}| market for | Cut-off, S*	*kg*	*Global*
Other materials	Concrete	*Concrete, normal {GLO}| market group for concrete, normal | Cut-off, S*	*m3*	*Global*
	Steel	*Reinforcing steel {GLO}| market for | Cut-off, S*	*kg*	*Global*
Plastic	Plastic usage	*Injection moulding {GLO}| market for | Cut-off, S*	*kg*	*Global*
	Plastic production	*Polyethylene terephthalate, granulate, amorphous {RoW}| production | Cut-off, S*	*kg*	*Global*

	Plastic	*Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | Cut-off, S*		*Global*
Transport	Transport of sludge	*Transport, freight, lorry 16-32 metric ton, euro6 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, S*	*tkm*	*European*
	Transport of infrastructure	*Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S*	*tkm*	*Global*
	Transport of dead fish	*Transport, freight, inland waterways, barge {RER}| market for transport, freight, inland waterways, barge | Cut-off, S*	*tkm*	*European*
Waste	Steel	*Steel and iron (waste treatment) {GLO}| recycling of steel and iron | Cut-off, S*	*kg*	*Global*
	Plastics	*Mixed plastics (waste treatment) {GLO}| recycling of mixed plastics | Cut-off, S*	*kg*	*Global*
	Sludge to biogas	Biowaste {RoW}| treatment of biowaste by anaerobic digestion | Conseq, S	kg	Global
	Dead fish to heat	Biowaste {GLO}| treatment of biowaste, municipal incineration | Conseq, S	kg	Global
Nutrient and smolt emissions to ocean		Phosphorus	Kg	Global
		Nitrogen	kg	Global
		Carbon dioxide	kg	Global
		DOC, Dissolved Organic Carbon	kg	Global
		Organic carbon	kg	Global
	Emissions of feces, urine, and feed waste generated during grow-out	Zinc	kg	Global
		Sodium chloride	kg	Global
		Cadmium	kg	Global
		Aluminium	kg	Global
		Lead	kg	Global
		Arsenic	kg	Global
		Molybdenum	kg	Global
		Iron II	kg	Global
		Potassium	kg	Global
		Calcium	kg	Global
		Magnesium	kg	Global
		Copper	kg	Global
		Manganese	kg	
		Hydrogen peroxide	kg	
		Nickel	kg	
		Sulphur	kg	
		Mercury	kg	

Appendix 3: Overview of the impacts on the marine ecotoxicity potential across selected technologies and cases presented in units of g 1,4DCB-eq per kg salmon at farm gate and with a breakdown on the nine main aggregated processes.



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