# A Comprehensive Review of the Factors Influencing the Environmental Impact of different Species bred in Closed Land-based Recirculating Aquaculture Systems


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Picture cover page: Grilled fish on a boat in the Philippines. Photo: Siri Samuelsson

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# Abstract

Today the future supply of seafood is threatened due to human activities which, among other things, has led to overfishing. However, more environmental friendly initiatives of producing seafood have emerged, such as Recirculating Aquaculture Systems (RASs). By analyzing the sensitivity analysis from six different Life Cycle Analysis (LCAs) on RASs, eight different factors that influence the environmental impact from RASs could be identified. These factors are; 1) By-products used, 2) Renewable electricity, 3) Global/local electricity mix, 4) Higher stocking density, 5) Nutrients emitted, 6) Crop-based feed, 7) Excluding land use change, 8) Feed conversion ratio (FCR) closer to 1. Whether the influence of each factor depended on the species being reared could not be determined, due to a large variation in the amount of factors addressed in each LCA. Renewable electricity was used as a factor in five LCAs and all five agreed that the use of renewable electricity reduced the environmental impact from fish reared in RAS. The variation in magnitude of these reductions could be explained by the location of each facility. Thus, the living conditions that each species require could not be determined as the cause of this variation. Crop-based feed did not lessen the environmental impact in all cases. The use of soybean meal increased the environmental impact when it was substituting krill meal. Further developments of LCA are needed to determine if the factors influence differ between different species.

**Keywords**
Recirculating aquaculture system; renewable electricity; Feed Conversion Ratio; environmental impact; freshwater eutrophication; climate change; land use; cumulative energy use; acidification

# Popular Abstract (Swedish)

## Förnybar el kan sänka miljöpåverkan från fisk som odlas på land

Den framtida tillgången till jordens resurser äventyras av hur människor idag och historiskt har utnyttjat de här resurserna. Vi ser redan idag hur människans agerande har påverkat miljön och de resurserna som vi lever av. Det är därför viktigt att vi utvecklar vårt sätt att leva mot ett mer hållbart levnadssätt.

Ett stort steg mot ett mer hållbart levnadssätt handlar om att upprätthålla en hållbar matproduktion. Därför har det här arbetet undersökt vilka faktorer som influerar miljöpåverkan från fisk som odlas på land och om de olika faktorernas påverkan skiljer sig mellan olika fiskarter. Fördelen med att identifiera de här faktorerna är att det underlättar framtida utveckling av fiskodling genom att belysa alternativ som leder till en mindre påverkan på miljön. Det här arbetet är särskilt fokuserat på ett landbaserat odlingssystem som kallas Recirkulerande Akvakultur System (RAS). RAS som odlingsmetod anses redan vara en mer miljövänlig metod jämfört med konventionellt fiske och kassodling men en konstant utvärdering av bättre alternativ inom matproduktion är alltid viktigt.

Det här arbetet har identifierat åtta olika faktorer som influerar miljöpåverkan från RAS, genom att analysera livscykelanalyser (LCAer) utförda på RAS. Dessutom redogör resultatet för huruvida de här faktorerna ökar eller minskar miljöpåverkan. Dock visade resultatet en stor variation i hur många faktorer som adresseras i varje LCA, vilket gjorde att skillnader mellan olika fiskarter inte kunde identifieras. Emellertid vittnar den stora variationen inom antalet adresserade faktorer om att ytterligare arbete krävs för att LCAer ska kunna bli jämförbara sinsemellan.

Trots den stora variationen av antalet adresserade faktorer i varje LCA fanns det en faktor som behandlades i majoriteten av LCAerna. Den faktorn som adresserades av flest LCAer var *Förnybar el*. Gemensamt för samtliga LCAer som adresserade *Förnybar el* var att användning av förnybar el minskade miljöpåverkan från fisken som odlas på anläggningen. Det visade sig också att skillnader i storleksordningen av minskningen mellan LCAerna inte berodde på vilken fiskart som odlades, utan var anläggningen låg geografiskt. Ett överraskande resultat som presenteras i arbetet berör användning av växtbaserat foder. Två LCAer presenterar, med hjälp av två olika faktorer, att användningen av soja i foder kan öka miljöpåverkan. I ett av fallen byts krillmjöl ut till sojamjöl, vilket leder till en ökad miljöpåverkan. Det betyder att ett växtbaserat foder, ur miljösynpunkt, inte nödvändigtvis är ett bättre alternativ än ett animaliskt foder.

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# 1. Introduction

All humans depend directly or indirectly on the oceans and their ecosystem services and resources (Intergovernmental Panel on Climate Change (IPCC, 2019). Human activities have used these functions for centuries and today these activities pose a threat to ensure that these ecosystem services and resources will be available in the future (IPCC, 2019; Lotze et al., 2006). The oceans have, for thousands of years, provided humans with resources, especially in terms of food (Withgott & Laposata, 2015). Lately, humans have been overharvesting these resources, leading to an unprecedented pressure on the oceans (Jackson et al., 2001; Myers et al., 2003). Somberly enough, is the old adage "there are always more fish in the sea"  no longer accurate.

The environmental impact from food production is one of the greatest contributors to the global environmental issues that we face today (Adegbeye, et al., 2020). However, more environmentally friendly initiatives are now entering the food production sector, with the hopes to diminishing the environmental impact from food (ibid). Today, seafood is seen as a promising alternative for a more sustainable diet (Bergman, et al., 2020). The reason for this is that the increasing production of seafood in closed land-based Recirculating Aquaculture Systems (RASs) can avoid many local environmental issues related to traditional open net-pen systems (Bergman, et al., 2020). Rearing fish in RAS provides a controlled environment where fish is stocked indoors in tanks and the water is purified by filtration before recirculated back to the system (Ahmed & Turchini, 2021). The technology of RAS has existed for more than 65 years and the first commercial RAS facility was built in Denmark during 1980 (ibid). Since 1980, RAS has been developed continuously and it is now an applied rearing method in several different countries all over the world (ibid).

Although production of fish in RASs relieves some aspects of the pressure on ocean fishery, the method of breeding fish through RASs still causes environmental impacts (Naylor, et al., 2000). The biggest contribution to environmental impacts from breeding fish in RASs generally comes from the production of feed (67-98 %) (Bergman et al., 2020). Apart from the fact that breeding carnivorous species require inputs of feed based on wild fish, which contributes to the pressure in ocean fishery that RASs aims to avoid, plant based feed also causes a great environmental impact (Naylor et al., 2000; Parolini et al., 2020).

Even though RASs is acknowledged to be a sustainable method of producing seafood, it is important to constantly develop these methods to ensure a sustainable future (Ahmed & Turchini, 2021). By researching the factors that influence the environmental impacts when breeding fish in closed land-based RASs, this study aims to identify the aspects of land-based production of seafood that can undergo further developments to lower the environmental impact. A continuously development of RASs towards a more sustainable production is of high importance to ensure the future sustainable supply of seafood. Nevertheless, this study aims to investigate potential factors that influence the environmental impact from different species reared in RAS. This part is intended to answer if the influences of the factors depend on each species living conditions or not.

## 1.1 Purpose and problem statements

The purpose of this study is to compile the factors that influence the environmental impact from breeding different species of fish in closed land-based Recirculating Aquaculture Systems. The scope of the study will include five environmental impact categories; i) Freshwater eutrophication, ii) Climate change, iii) Land use, iv) Cumulative energy use and v) Acidification. These five categories are chosen to include a certain breadth of the environmental impact of RASs and commonly used in Life Cycle Analysis (LCAs) of RASs (Henriksson et al., 2012).

### 1.1.1 Problem statements

1. Which factors affect the environmental impact when breading fish in closed land-based Recirculating Aquaculture Systems?
2. Does the influence of each factor differ between different species?

### 1.1.2 Hypothesis

1. Depending on which living conditions that the species require, the factors that influence the environmental impact from rearing each species will differ.
2. The use of renewable energy will decrease the environmental impact in all impact categories.
3. Crop-based feed will decrease the environmental impact in all impact categories.

### 1.1.3 Delimitations

This study is delimited to only review those LCAs, on different fish species reared in RAS, that are available on Web of Science. Additional LCAs on this subject are available, however, most LCAs are performed by consulting firms and are usually not published in databases. An impartial inclusion of such LCAs was not possible within the time frame of this study.

In addition, the included LCAs are delimited on the basis of the requirements in the study selection criteria's (see section 2.1.1 Study selection criteria).

# 2.Method and search results

A qualitative systematic literature review was conducted, inspired by the Reporting standards for Systematic Evidence Syntheses (ROSES) methodology, to gain more insight on which factors that are of interest when evaluating environmental impacts from fish products produced through RASs (Haddaway et al., 2017). Gathering Life Cycle Analysis (LCA) on fish bred in RAS and analyzing each sensitivity and scenario analysis could identify factors that influence the environmental impact. Accepted factors were exclusively factors compared against the baseline scenarios (i.e. the prevailing scenarios in which the LCAs were performed), in order to understand how the environmental impact from different species bred in existing RASs are influenced by changes of these factors.

## 2.1 Search strategy

Searches were performed on Web of Science (all databases) to identify relevant Life Cycle Analyses (LCAs) on RASs published between 2012-2022. The searches were done on titles, keywords and abstract in English and the search string for LCAs on RASs was composed by three substrings: *Life Cycle Analysis* (1), *Recirculating Aquaculture Systems* (2) and *aquaculture* (3). The substrings were connected with the Boolean operator 'AND' as follows: 1 AND 2 AND 3, including synonyms and acronyms (Table 1).

**Table 1**

The search string for the literature search, including keywords and scope of the search range for Life Cycle Analysis on Recirculating Aquaculture Systems. The numbers in "Selection 1,2 & 3 account for the amount of LCAs that passed the filters.

| Database: Web of Science | Keywords | Scope of the search range | Selection 1 | Selection 2 | Selection 3 |
|---|---|---|---|---|---|
| #1 | ("LCA" OR "Life Cycle Analysis") AND ("RAS" OR "Recirculating Aquaculture Systems") AND ("fish farming*" OR aquaculture*) | | 21 | | |
| #2 | #1 | **Filter:** Published between 2012-2022 | | 19 | |
| #3 | #2 | **Filter:** Relevance to this study, in terms of the criteria's mentioned in section *2.1.1 Study selection criteria* | | | 6 |

### 2.1.1 Study selection criteria

The process of systematically refining the reports that were included in this review is illustrated in table 1. First the results from the search string were filtered on year of publication (2012-2022), to ensure the relevance of this study, in terms of investigating modern LCAs on RASs. This was necessary in order to map the potential of improvement within modern RAS facilities. The screening focused on titles, abstracts and methods and resulted in 19 reports being fully reviewed. The inclusion and exclusion criteria's was applied in the screening of titles, abstracts, methods and full-text and resulted in six reports being eligible for this study (Table 2).

Table 2
Inclusion and exclusion criteria used in the literature review

| | Inclusion | Exclusion |
|---|---|---|
| RAS | Different species of fish bred in RAS | Species that are not fish but are bred in RAS |
| | Actual farms | Simulations of fictional RAS |
| Assessments | Assessments that use LCA as method | Studies that use other methods than LCA |
| | Quantitative assessments of environmental impacts | Qualitative assessments |
| | The LCA include a sensitivity and/or scenario analysis that compair to baseline scenario | The LCA do not include a sensitivity and/or scenario analysis |
| | | The sensitivity and/or scenario analysis compair to another scenario than the baseline scenario |
| | One or several of the environmental impact categories are included in the sensitivity and/or scenario analysis | The sensitivity and/or scenario analysis do not include any of the five environmenlat impact categories chosen in this study |

In addition to the inclusion and exclusion criteria's should the selected climate impact categories of this study be expressed in the units listed in table 3. There is a certain variation in how these five categories are named in different LCAs, therefore, by only including these six units, the information drawn from each LCA can be ensured to be the wanted information. Nor will this study include factors that relate to how allocations of environmental burdens are done. Allocation of environmental burdens are a recognized issue within developments of LCAs, especially within aquaculture, hence they will not be included (Azapagica & Cliftb., 1999; Svanes et al., 2011).

Table 3:
Preferred units for calculated environmental impact within selected environmental impact categories.

| Environmental impact category | Unit |
|---|---|
| Freshwater eutrophication | kg $PO_4$ eq. or kg P eq. |
| Climate change | kg $CO_2$ eq. |
| Land use | $m^2a$ |
| Cumulative energy demand | MJ |
| Acidification | Kg $SO_2$ eq. |

## 2.2 Ethical reflection

This study will highlight two ethical issues. Firstly, the method of breeding fish in land-based Recirculating Aquaculture Systems itself, in particular that large amounts of fish is bred in small basins compared to the living conditions in the species' natural habitat. Connected to this is also the issue of how the climate footprint is affected by the amount of individuals per area.

Secondly, there is an ethical dilemma with this study contributing to giving RASs a bad rumor and that it no longer will be considered a sustainable method for producing seafood. However, this will be handled by arguing for the great importance of constantly developing systems towards a more sustainable development. Especially by aiming to present suggestions on how the climate footprint can be improved.

# 3. Results

The six reports being eligible for this study resulted in a comparison between, in total, five species bred in RASs (Table 4). Each LCA included in this study had the system boundary "cradle to farm-gate", meaning that the evaluation of the species environmental impact were performed on the total production of each species, up to the point where the product leaves the farm gate of the RAS facility (Groen et al., 2014).

**Table 4**
The species that are involved in this study, including the references to each LCA and origin of the RAS.

| Species | Amount of LCAs | Source | Origin |
|---|---|---|---|
| **Tilapia** | 2 | **#1:** Bergman, K., Henriksson, P. J., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G. & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy tradeoff: life cycle assessment of warmwater fish farming in Sweden. *Environmental science & technology*, *54*(24), 16062-16070. DOI: 10.1021/acs.est.0c01100<br>**#2:** Boxman, S. E., Zhang, Q., Bailey, D., & Trotz, M. A. (2017). Life cycle assessment of a commercial-scale freshwater aquaponic system. Environmental Engineering Science, 34(5), 299-311. DOI: 10.1016/j.aquaeng.2020.102130 | **#1:** Sweden<br>**#2:** U.S. Virgin Islands |
| **Clarias** | 1 | Bergman, K., Henriksson, P. J., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G. & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy tradeoff: life cycle assessment of warmwater fish farming in Sweden. Environmental science & technology, 54(24), 16062-16070. DOI: 10.1021/acs.est.0c01100 | Sweden |
| **Atlantic Salmon** | 1 | Song, X., Liu, Y., Pettersen, J. B., Brandão, M., Ma, X., Røberg, S., & Frostell, B. (2019). Life cycle assessment of recirculating aquaculture systems: A case of Atlantic salmon farming in China. *Journal of industrial ecology*, *23*(5), 1077-1086. DOI: 10.1111/jiec.12845 | China |
| **Eurasian perch** | 1 | Cooney, R., Tahar, A., Kennedy, A., & Clifford, E. (2021). The dilemma of opportunity in developing a life cycle assessment of emerging aquaculture systems-a case study of a Eurasian perch (Perca fluviatilis) hatchery recirculating aquaculture system. *Aquaculture*, *536*, 736403. DOI: 10.1016/j.aquaculture.2021.736403 | Ireland |
| **Rainbow trout** | 2 | **#1:** Samuel-Fitwi, B., Nagel, F., Meyer, S., Schroeder, J. P., & Schulz, C. (2013). Comparative life cycle assessment (LCA) of raising rainbow trout (Oncorhynchus mykiss) in different production systems. Aquacultural Engineering, 54, 85-92. DOI: 10.1016/j.aquaeng.2012.12.002<br>**#2**: Dekamin, M., Veisi, H., Safari, E., Liaghati, H., Khoshbakht, K., & Dekamin, M. G. (2015). Life cycle assessment for rainbow trout (Oncorhynchus mykiss) production systems: a case study for Iran. Journal of Cleaner Production, 91, 43-55. DOI: 10.1016/j.jclepro.2014.12.006 | **#1:** Denmark<br>**#2:** Iran |

Eight different factors were identified to influence the environmental impact within the five studied environmental impact categories. These factors were; 1) *By-products used,* 2) *Renewable electricity,* 3) *Global/local electricity mix,* 4) *Higher stocking density,* 5) *Nutrients emitted,* 6) *Crop-based feed,* 7) *Excluding land use change,* 8) *Feed conversion ratio (FCR) closer to 1.* The factors were identified by analyzing the sensitivity analyzes of each LCA.

The first factor, *by-products used*, included the treatment of by-products from producing the final product, such as the remaining biomass after filleting (Bergman et al., 2020). This factor was only present in one LCA, meaning that filleting was performed within the farm gates of the RASs facility (ibid). The second factor, *renewable electricity,* included a mix of renewable electricity that had a higher percentage of renewable electricity sources than the baseline scenario (Bergman et al., 2020; Boxman et al., 2017; Dekamin et al., 2015; Samuel-Fitwi et al., 2013 & Song et al., 2019a). The third factor, *Global/local electricity mix,* represented a mix of renewable and fossil electricity sources (Bergman et al., 2020; Boxman et al., 2017). The fourth factor, *Higher stocking density,* related to an optimization of the stocking density compared to the baseline scenario (Song et al., 2019a). The fifth factor, *Nutrients emitted,* regarded emission of waste nutrients to nature (Bergman et al., 2020). The sixth factor, *Crop-based feed,* included both a 100 % crop based feed and feed where the animal components were partly substituted with crop (Bergman et al., 2020; Song et al., 2019a). The seventh factor, *Excluding land use change,* is used to demonstrate the influence of deforestation on the environmental impact (Bergman et al., 2020). In this factor it is done by excluding the emissions of Greenhouse gases (GHG) from land transformation (Bergman et al., 2020). The last factor regard feed conversion ratio (FCR). FCR is a measure of livestock production efficiency, i.e. the weight of the feed intake divided by weight gained by the animal (Skinner-Nobel & Teeter, 2003). *Feed conversion ratio (FCR) closer to 1,* represented a scenario where the FCR was more efficient than the baseline scenario (Cooney et al., 2021; Dekamin et al., 2015; Samuel-Fitwi et al., 2013 & Song et al., 2019a). Namely, when distribution of feed is being pinpointed to avoid losses.

The result of the comparisons between relative changes and the baseline scenarios of each factor in the analyzed LCAs were sorted in to three categories; 1) Depends, 2) Increasing and 3) Decreasing. When the results of the sensitivity analysis showed a decrease, this meant that that factor had a positive effect on the environmental impact compared to the baseline scenario, and vice versa were applied when the factor showed an increase. Assessments with conditional outcomes are classified as ‘depends’ and implies that the influence of the factor on the environmental impact are dependent on contextual and assessment conditions. These conditions will be further discussed in this study. A summary of the result can be found in table 5.

**Table 4**

Summarized result of how the factors influenced the environmental impact categories. The numbers in the columns for each species account for the amount of LCAs that present the factors influence on the environmental impact to either increase, decrease or depend. The column named 'Total' illustrates the factors influence on the environmental impact when all the species are summarized.

| Environmental impact categories | Comparison to baseline scenario | Species | | | | | | | | | | | | | | | Total | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tilapia | | | Clarias | | | Atlantic Salmon | | | Rainbow trout | | | Eurasian perch | | | | | |
| | Factors | Depends | Increasing | Decreasing | Depends | Increasing | Decreasing | Depends | Increasing | Decreasing | Depends | Increasing | Decreasing | Depends | Increasing | Decreasing | Depends | Increasing | Decreasing |
| Freshwater eutrophication | By-products used | | | 1 | | | 1 | | | | | | | | | | | | 2 |
| | Renewable electricity | | | 2 | | | 1 | | | 1 | | | 2 | | | | | | 6 |
| | Global/local electricity mix | | 2 | | | 1 | | | | | | | | | | | | 3 | |
| | Higher stocking density | | | | | | | | | 1 | | | | | | | | | 1 |
| | Nutrients emitted | | 1 | | | 1 | | | | | | | | | | | | 2 | |
| | Crop-based feed | | | 1 | | | | 1 | | | | | | | | | 1 | | 1 |
| | FCR closer to 1 | | | | | | | | | 1 | | | 1 | | | 1 | | | 3 |
| Climate change | By-products used | | | 1 | | | 1 | | | | | | | | | | | | 2 |
| | Renewable electricity | | | 2 | | | 1 | | | 1 | | | 2 | | | | | | 6 |
| | Global/local electricity mix | | 1 | 1 | | 1 | | | | | | | | | | | | 2 | 1 |
| | Excluding land use change | | | 1 | | | 1 | | | | | | | | | | | | 2 |
| | Higher stocking density | | | | | | | | | 1 | | | | | | | | 1 | |
| | Crop-based feed | | | 1 | | | | | | 1 | | | | | | | | | 2 |
| | FCR closer to 1 | | | | | | | | | 1 | | | 1 | | | 1 | | | 3 |
| Land use | By-products used | | | 1 | | | 1 | | | | | | | | | | | | 2 |
| | Renewable electricity | | 1 | 1 | | | 1 | | | | | | 1 | | | | | 1 | 3 |
| | Global/local electricity mix | | 1 | 1 | | | 1 | | | | | | | | | | | 1 | 2 |
| | Crop-based feed | | | 1 | | | | | | | | | | | | | | | 1 |
| Cumulative energy demand | By-products used | | | 1 | | | 1 | | | | | | | | | | | | 2 |
| | Renewable electricity | | | 2 | | | 1 | | | 1 | | | | | | | | | 4 |
| | Global/local electricity mix | | 1 | 1 | | 1 | | | | | | | | | | | | 2 | 1 |
| | Higher stocking density | | | | | | | | | 1 | | | | | | | | | 1 |
| | Crop-based feed | | | 1 | | | | | | 1 | | | | | | | | | 2 |
| | FCR closer to 1 | | | | | | | | | 1 | | | | | | 1 | | | 2 |
| Acidification | Renewable electricity | | | 1 | | | | | | 1 | | | 2 | | | | | | 4 |
| | Global/local electricity mix | | | 1 | | | | | | | | | | | | | | | 1 |
| | Higher stocking density | | | | | | | | | 1 | | | | | | | | | 1 |
| | Crop-based feed | | | | | | | | | 1 | | | | | | | | | 1 |
| | FCR closer to 1 | | | | | | | | | 1 | | | 1 | | | 1 | | | 3 |

## 3.1 Freshwater eutrophication

In general, it is evident that the influence of the factors on the environmental impact category *Freshwater eutrophication* is scattered and inconsistent when comparing between different species (Table 5). The inconsistency between different species is the outcome of variation between which environmental impact categories and factors that are of focus in each LCAs. However, there is consistency in how a few factors influence the environmental impact in the freshwater eutrophication category, despite the scattered spread in which factors that were reported to influence the environmental impact in this category.

### 3.1.1 Renewable electricity

Five LCAs reported that a switch to an electricity source with a higher percentage of renewable electricity than the baseline scenario results in a decrease of the environmental impact in this category (see references given in Table 4; Table 5). The extent of the reduction in environmental impact, after a switch to a renewable electricity source, depended on the proportions of renewable electricity in the baseline scenario (ibid). Bergman et al. (2020) reported that the decrease in environmental impact, in the freshwater eutrophication category, after switching to an electricity source with 100 % renewable electricity were limited when rearing Tilapia and Clarias. Bergman et al. (2020) argued that this was due to the high percentage of renewable electricity in the Swedish electricity mix, which was used in the baseline scenario. Similar extent of reduction was reported by Song et al. (2019a) when breading Atlantic salmon in RAS in China. In that case, the switch to a higher percentage of renewable electricity transpired to 20 % of the electricity from coal-fired power plants, in the baseline scenario, being replaced with wind-based electricity, leading to a 12 %  reduction of the environmental impact in this category (Song et al., 2019a). The small reduction of the environmental impact from freshwater eutrophication in this case can be explained by 55.3 % of the electricity sources still remained fossil after 20 % of the electricity from coal-fired power plants were replaced with wind-based electricity (Song et al., 2019b).

When Rainbow trout were reared in RAS there was a  higher reduction of the environmental impact from freshwater eutrophication, because a higher percentage of renewable energy was used RAS (Dekamin et al., 2015; Samuel-Fitwi et al., 2013). For this species, a switch to a higher percentage of renewable energy corresponded to a reduction of the environmental impact by 29-45 % (ibid). The high reduction of the environmental impact from freshwater eutrophication in these three cases can be explained by the baseline electricity source being a 100 % replaced by renewable electricity (ibid)

However, when breading Tilapia in an aquaponic in U.S. Virgin Islands, which is a specific type of RAS that combines recirculating aquaculture technologies with hydroponic plant production, higher diminishments were received (Boxman et al., 2017). The switch to a higher percentage of renewable electricity decreased the environmental impact of freshwater eutrophication with 171 %, although the absolute decrease in this case was relatively small (ibid).

### 3.1.2 Global/local electricity mix

Two different LCAs, which together covered the environmental impact from two species bred in RAS, reported that when the electricity source used in the baseline scenario were switched to a global or a local electricity mix it resulted in an increase of the environmental impact from freshwater eutrophication (See given references in Table 4; Table 5). Both Bergman et al. (2020) and Boxman et al. (2017) presented that using a global or local electricity mix would result in the environmental impact from freshwater eutrophication being around 4.5 times higher than the baseline scenario for the species Tilapia. In both cases could this high increase be explained by the mix of electricity sources in the baseline scenario being consisted with less fossil sources than the global or local electricity mix (Bergman et al., 2020; Boxman et al., 2017).

For Clarias however, which was reared in the same facility as Tilapia, the global electricity mix did not show the same degree of increase when the baseline electricity source was switched (Bergman et al., 2020). Bergman et al. (2020) reported that the switch to a global electricity mix corresponded to an increase two times higher than the environmental impact of the baseline scenario for Clarias.

### 3.1.3 Feed conversion ratio (FCR) closer to 1

As for the factor *Global/local electricity mix*, only three LCAs addressed the sensitivity of the factor *Feed conversion ratio closer to 1* in their sensitivity analysis (See references given in Table 4; Table 5). Song et al. (2019a) argued that optimizing the FCR when rearing Atlantic salmon, from 1.45 (baseline scenario) to 1.1, would decrease the environmental impact from freshwater eutrophication by 3.6 %.

Dekamin et al. (2015) and Cooney et al. (2021) reported higher reductions of the environmental impact from freshwater eutrophication. When breading Rainbow trout in RAS, Dekamin et al. (2015) presented that an optimization of the FCR from 1.46 to 1 corresponded with decreased environmental impact from freshwater eutrophication by ~35 %. A decrease on a similar scale was presented by Cooney et al. (2021) after the FCR were optimized from 1.5 to 1. Cooney et al. (2021) reported that this optimization decreased the environmental impact from freshwater eutrophication by 42 % when rearing perch in RAS.

## 3.2 Climate change

The results of which factors that influence the environmental impact from the climate change category are equally scattered as in the freshwater eutrophication category (Table 5). This too is due to the inconsistencies of which environmental impact categories and factors that are addressed in each LCA. Despite that, a certain pattern between a few of the factors can be discerned.

### 3.2.1 Renewable electricity

As in the case of renewable electricity in the *Freshwater eutrophication* category, five of the LCAs reported that by shifting electricity source to one with a higher percentage of renewable sources, the environmental impact from the climate change category decreased (See references given in Table 4; Table 5). The magnitude of the reported decrease in these five LCAs varies between 1-90 % (See references given in Table 4). Bergman et al. (2020) reported the lowest decrease after the baseline electricity source had been switched to a 100 % renewable source, 2 % decrease when rearing Tilapia and 1 % decrease when rearing

Clarias. However, in this case the electricity source in baseline scenario already consisted of a high percentage of renewable electricity, hence the low effect (Bergman et al., 2020). Song et al. (2019a) presented a 14.6 % decrease of the environmental impact from Atlantic salmon in the climate change category when 20 % of the electricity from coal-fired power plants were replaced by wind-based electricity.

Boxman et al. (2017), Dekamin et al. (2015) and Samuel-Fitwi et al. (2013) presented higher effects on the environmental impact after a switch to renewable electricity. The environmental impact from rearing Tilapia in an aquaponic in U.S. Virgin Islands decreased with 36 % in the climate change category after the electricity source had been replaced by a renewable source (Boxman et al., 2017). Dekamin et al. (2015) argued that the environmental impact from Rainbow trout decreased by 81 % in this category after the electricity source had been replaced by a renewable one. Samuel-Fitwi et al. (2013) presented a 90 % decrease of the environmental impact from Rainbow trout in this category after replacing the baseline electricity source with a renewable source.

### 3.2.2 Global/local electricity mix

Two LCAs included the global/local electricity mix factor in their sensitivity analysis (See references given in Table 4; Table 5). However, the result of how it affects this category differ (Table 5). Regarding Tilapia and clarias, which were bred in a RAS facility located in Sweden, a switch to a global electricity mix resulted in an increase of the environmental impact, from the climate change category, by 91 & 25 % respectively (Bergman et al., 2020). Bergman et al. (2020) argues that the main driver for this increase is the large portion of renewable electricity sources in the baseline scenario. On similar grounds, Boxman et al. (2017) sensitivity analysis shows a 14 % reduction of the environmental impact from the climate change category after the baseline electricity source had been replaced by a local electricity mix. Again, this is explained by the composition of the baseline electricity source and in this case, the local electricity mix had a lower percentage of non-renewable electricity sources (Boxman et al., 2017).

### 3.2.3 Feed conversion ratio (FCR) closer to 1

The optimization of the FCR showed a decrease of the environmental impact from the climate change category slightly smaller than the decrease of impact in the freshwater eutrophication category (Song et al., 2019a; Cooney et al., 2021; Dekamin et al., 2015). By optimizing the FCR, when rearing Atlantic salmon, from 1.45 (baseline scenario) to 1.1 Song et al. (2019a) reduced the environmental impact by 7.3 %. Cooney et al. (2021) however accounted for a 20 % reduction after the FCR had been optimized from 1.5 to 1. Dekamin et al. (2015) also presented a reduction on a similar scale to Cooney et al (2021). By optimizing the FCR from 1.46 to 1, Dekamin et al. (2015) reduced the environmental impact of Rainbow trout by 22 % in the climate change category.

## 3.3 Land use

Following the pattern from the categories above, the results from this category are scattered and, in addition, fewer LCAs presents impacts from this category (Table 5). Three LCAs used *Land use* as a category in their sensitivity analysis and together they report the influence of four different factors (See references given in Table 4; Table 5).

### 3.3.1 Renewable electricity

Renewable electricity had an overall lesser influence on the environmental impact of land use when comparing percentage of increase/decrease to the two categories above. Boxman et al. (2017) presented, in this category, a 4 % increase of the environmental impact after the baseline electricity mix had been replaced with a renewable electricity source. Bergman et al. (2020) however reported a 11 % decrease for Tilapia and a 3 % decrease for Clarias after the replacement of electricity source. In the case of Rainbow trout did the renewable electricity source correspond to a 37 % decrease of the environmental impact of the land use category (Samuel-Fitwi et al., 2013).

### 3.3.2 Global/local electricity mix

The effect of using a global/local electricity mix had, in one case, a surprising influence on the environmental impact from Tilapia and Clarias in this category (Bergman et al., 2020). Bergman et al. (2020) reported a decrease of the environmental impact from Tilapia and Clarias in the *Land use* category when a global electricity mix was used. The actual decreases for these species corresponded to 7 % for Tilapia and 2 % for Clarias (Bergman et al., 2020). The result of Boxman et al. (2017) were more expected and showed an increase by 11 % for Tilapia reared in an aquaponic.

## 3.4 Cumulative energy demand

The frequency of how often each factor was included in the sensitivity analysis of the analyzed LCAs was considerably low in this category (Table 5). Most of the factors were only included in one or two LCAs, resulting in a scattered result from this category (See references given in Table 4; Table 5).

### 3.4.1 Renewable electricity

Despite the scattered result in this category did three LCAs use renewable electricity as a factor in their sensitivity analysis (See references given in Table 4; Table 5). All three LCAs concluded that the environmental impact decreased in this category after the baseline electricity source had been replaced with a renewable source (See references given in Table 4; Table 5). The percentage of decrease in these cases was 43 % for Tilapia (Boxman et al., 2017), 7.1 % for Atlantic salmon (Song et al., 2019a), 35 % for Tilapia and 17 % for Clarias (Bergman et al., 2020).

### 3.4.2 Global/local electricity mix

The Global/local electricity mix factor was only included by two LCAs in this environmental impact category (See references given in Table 4; Table 5). These two reports included LCAs performed on Tilapia reared in RAS facilities. However, the result on how this factor affected environmental impact differed between the two LCAs (See references given in Table 4; Table 5). Boxman et al. (2017) displayed a 15 % decrease of the environmental impact of the cumulative energy demand, when a local electricity mix was used. The opposite effect was reported by Bergman et al. (2020), showing that the global electricity mix increased the environmental impact by 21 % for Tilapia and 10 % for Clarias.

The differences in how this factor influenced the environmental impact depend on the electricity sources used in the baseline scenario (Bergman et al., 2020; Boxman et al., 2017).

## 3.5 Acidification

The results are similar to the results from all of the other chosen categories in this study (Table 5). Not all LCAs have used all the factors in their sensitivity analysis, which results in the result being very fragmented.

### 3.5.1 Renewable electricity

The four LCAs that included renewable electricity as a factor in their sensitivity analysis were consistent in renewable electricity reducing the environmental impact (See references given in Table 4; Table 5). Song et al. (2019a) reported an 11.8 % decrease after 20 % of the electricity from coal-fired power plants had been replaced by wind-based electricity. Higher reductions were presented by Boxman et al. (2017); Dekamin et al. (2015); and Samuel-Fitwi et al. (2013), but in those cases, the baseline electricity source were fully replaced by a renewable source. The decreases in these cases corresponded to 45 % for Tilapia, reported by Boxman et al. (2017), 56 % for rainbow trout, reported by Dekamin et al. (2015) and 83 %, also for rainbow trout but reported by Samuel-Fitwi et al. (2013).

### 3.5.2 Feed conversion ratio (FCR) closer to 1

Three LCAs used *FCR closer to 1* as a factor in this category (See references given in Table 4; Table 5). All three presented that an optimization of the FCR decreased the environmental impact from acidification (See references given in Table 4; Table 5). By optimizing the FCR, when rearing Atlantic salmon, from 1.45 (baseline scenario) to 1.1 Song et al. (2019a) diminished the environmental impact from acidification by 11.4 %. Cooney et al. (2021) and Dekamin et al. (2015) however, accounted diminishments in the order of 18 % and 38 % when the FCR were optimized from 1.5 and 1.46 to 1.

## 3.6 Remaining factors

The remaining factors that are not mentioned in the sections for each category were not included in several of the studied LCAs, hence their effects are also not accounted for. However, the influences on the environmental impact are worth mentioning in order to keep developing RAS towards a more sustainable rearing process.

Bergman et al. (2020) presented the effect of utilizing by-products from the fileting higher in the waste-hierarchy. This reduced the environmental impact from each category (Bergman et al., 2020). *By-products use* were only used as a factor by Bergman et al. (2020) due to filleting performed on the RAS facility only occurred in this case (See references given in Table 4; Table 5). Two additional factors were addressed only by Bergman et al. (2020), *nutrients emitted* and *excluding land use change.* Regarding the factor *nutrients emitted*, it examined the usefulness of the biological filters that are applied to use nutrients as a fertilizer (Bergman et al., 2020). When these filters were removed and the nutrients were instead emitted directly into nature, the environmental impact increased significantly of "Freshwater eutrophication" (Table 5)(Bergman et al., 2020). Although its effect was not explored, Bergman et al. (2020) also highlighted the potential of how holding sludge affect emissions of Greenhouse gases (GHG).

By using the factor *excluding land use change,* Bergman et al. (2020) excluded the emissions of GHG from land transformation, primarily to prove the influence of deforestation for the benefit of soy production. Ultimately, this exclusion reduced the emissions of GHG from Tilapia and Clarias roughly by half, demonstrating the large impact of feed based on soy, as well as poultry feed fed soy (Bergman et al., 2020). A similar factor, *crop-based feed*, were also connected to the impact from soymeal in feed. *Crop-based feed* were used as a factor in two cases and related to all of the environmental impact categories in this study (See references given in Table 4; Table 5). Although crop-based feed generally decreased the environmental impact in these two cases, its influence seemed to be dependent on what kind of crop the feed would consist of (Bergman et al., 2020) and what kind of feed the crop-based feed would substitute for (Song et al., 2019a). In some categories investigated by Song et al. (2019a), krill meal substituted with soybean meal increased the environmental impact.

The last factor that remains is *Higher stocking density.* This factor were only mentioned by Song et al. (2019a) and is interfering with this study's ethical reflection by compromising the living conditions of the species to obtain an optimized stocking density. The baseline stocking density in this case was 24.2 $kg/m^3$. Song et al. (2019a) investigated how two higher stocking densities would influence the environmental impact, 60 $kg/m^3$ and 45 $kg/m^3$, which was the designed stocking density of that facility. Both optimized stocking densities decreased the environmental impact in the categories they were related to (Table 5). However, the difference between a stocking density of 60 $kg/m^3$ and 45 $kg/m^3$ were minimal, indicating that the benefit of compromising the species' living conditions is not particularly great in this case (Song et al., 2019a).

# 4. Discussion

The results of this study present eight different factors that influence the environmental impact in the five chosen categories (Table 5). These factors were; 1) *By-products used,* 2) *Renewable electricity,* 3) *Global/local electricity mix,* 4) *Higher stocking density,* 5) *Nutrients emitted,* 6) *Crop-based feed,* 7) *Excluding land use change,* 8) *Feed conversion ratio (FCR) closer to 1.* Most of these factors relate to inventory choices. Meaning that they refer to choices that are made on the RAS facility, such as choice of feed, how by-products are handled, densification of individuals, optimization of the feeding and use of biological filters. The factors that regard electricity are factors that refer to context, in the sense that those who operate the RAS facilities do not have full control over changes in these factors. Systematic changes within the electricity supply are therefore required if RAS facilities are to be able to lower their environmental impact from electricity use (Bergman et al., 2020; Boxman et al., 2017; Dekamin et al., 2015; Samuel-Fitwi et al. & 2013; Song et al., 2019a). The results of this study shows that most RAS facilities included in this study would reduce their environmental impact by using renewable electricity, regardless of the species bred (Table 5). However, the magnitude of the reduction depends on the conditions prevailing in the baseline scenario. Despite that the RAS facilities are located in different countries, the results of this study displays an incentive for a global systematic change of electricity supply, towards a more renewable dominated supply. Previous research regarding the positive affect of renewable electricity confirms this conclusion (Breitenstein & Hicks., 2022; Chen et al., 2020; Ghamkhar et al., 2020; Harrison & Whittington., 2002; Hou et al., 2022). Moreover, the results indicates that a switch to renewable electricity leads to a greater reduction of the environmental impact in some locations and less in others. For example, the RAS facility located in Sweden did not benefit as much as the facility located in Iran (Bergman et al., 2020; Dekamin et al., 2015). This insinuates that an expansion of renewable electricity sources leads to greater reductions for facilities located in countries with less established sources of renewable electricity. It is therefore proposed that the expansion should be focused on countries in which it makes the greatest difference.

Although a switch to renewable electricity had the same effect on most of the species (decreasing), this comparison was not applicable for the remaining factors. Leading to the results of this study not being completely in line with the expected outcome, particularly regarding the second problem statement. Essentially, there are too many knowledge gaps to determine whether the influence of each factor differ between different species or not (Table 5). The variation within the amount of factors that are included in each sensitivity analysis makes it impossible to answer the second problem statement. However, it is reasonable to deduce that the results of this study highlight this inconsistency as an improvement potential within LCAs performed on RAS. Previous studies have too acknowledged the need for a more standardized implementation of LCAs performed on aquaculture (Henriksson et al., 2012; Samuel-Fitwi et al., 2012).

The issues highlighted in previous research mainly regard differences that impact the quantitative output of emissions, such as choice of functional unit, system boundaries, impact assessment methods, allocation and data sourcing (Henriksson et al., 2012). Variation within these phases makes comparisons of quantitative output of emissions impossible without conversion of functional units, etc. (ibid). Furthermore, Henriksson et al. (2012) have also recognized the lack of complete sets of sensitivity analyses among LCAs on aquaculture. Inclusion of a sensitivity analysis is an essential part of the final interpretation in a LCA and it is also required by The International Organization of Standardization (ISO) standards (Groen et al., 2014; Henriksson et al., 2012). Yet, there are no guidelines on how to produce an appropriate sensitivity analysis (Groen et al., 2014). As shown in this study, the majority of the LCAs only address a few factors in their sensitivity analysis (Table 5). A strong argument in favor of including multiple factors in the sensitivity analysis is based on the transparency of uncertainties (Djekic et al., 2019). A large sum of the data that is used in a LCA is gathered from various databases (ibid). By including multiple factors that together relate to the majority of the input variables, the quality of input data and its influence on the final outputs can be determined (Djekic et al., 2019; Wei et al., 2015).

Despite the inconsistency within the reviewed articles, some of the factors grouped as *inventory choices* had a surprising influence on the environmental impact. The use of crop-based feed had an increasing effect in one case, when soybean meal was used as a substitute for krill meal (Song et al., 2019a). Soybean meal is a commonly used component in several sorts of feed (Sales & Britz, 2001; Selaledi et al., 2020). It is high in protein and are therefore a good substitute or compliment to animal feed (Sales & Britz, 2001). Today, and historically, rainforests in South America is being deforested in favor of soybean cultivation, causing tremendous environmental impact (Dreoni et al., 2022). This is already a known fact, but so is also the environmental impact of fish meal (Naylor et al., 2000), making the results of Song et al. (2019a) particularly interesting. Other crop-based feed components that could substitute for soy bean in feed, with less environmental impact, are fava beans and peas (Bergman et al., 2020).

The amount of search result gained in this study is highly influenced by the study's selection criteria's, but also by the chosen search engine (Web of Science). The initial search result (21 LCAs) was surprisingly few, which suggests that LCA on RAS are either published on specific databases or is yet not an established method within aquaculture. Since the search result got refined from 21 to 6 LCAs by applying the selection criteria's, it is credible to contend that a wider search range would improve the results of this study. Future studies should improve this type of review by gathering more LCAs through several different search engines, including a wider timeframe regarding year of publication, including additional environmental impact categories and accepting multiple units for those (if conversion is possible). In addition, the Gioia method of systematically reviewing large amounts of data is recommended for future qualitative research on RAS (Gioia et al., 2013). For time-limited reasons, this method could not be applied in this study.

# 5. Conclusions

Eight factors were identified to affect the environmental impact when breading fish in closed land-based Recirculating Aquaculture Systems. These factors could later be categorized as; *Inventory choices* and *Systematic changes.* However, the results from the factors included in *Inventory choices* were too inadequate to draw any conclusions about.

- Five out of six LCA addressed the factor renewable electricity. They all agreed on that renewable electricity decreases the environmental impact from every environmental impact category.

- No difference in influence between different species could be identified in the *renewable electricity factor*. Rather, the magnitude of diminishment, after using renewable electricity, depended on the prevailing electricity sources in each baseline scenario.

- Crop-based feed do not lessens the environmental impact in all cases. On the contrary, the use of soy bean meal can increase the environmental impact if it is substituting krill meal.

- Due to the inadequate reporting of the majority of the factors, this study concludes that developments of LCA on aquaculture is well needed. Especially inclusion of complete sets of sensitivity analyses.

- Future research can improve the method of this study by broadening the selection criteria's to include more LCAs on RAS.

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