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# The Environmental Impact of Partial Substitution of Fish-Based Feed with Algae- and Insect-Based Feed in Salmon Farming

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**Abstract:** One of the key challenges for aquaculture is to reduce "fishing-for-feed". Alternative fish feeds need to be environmentally assessed to ensure they are sustainable. The present research consisted of an attributional LCA to (i) estimate the impact on salmon farming of a partially algal–insect-based diet vs a conventional fish meal/fish oil-based diet, (ii) identify the contribution of each process to the environmental impacts of the whole fish farming system, and (iii) identify potential improvements in the algal–insect value chain through sensitivity analysis of various algal–insect production pathways. The study shows that use of algal–insect-based feed resulted in a higher impact for most of the environmental impact categories due to fish feed production, particularly for soybean, insect, and algal meal. This points to the need to optimise production chains for new fish feed ingredients. Algal meal production using sugarcane sugar and optimised technology and insect meal using exhaust heat and renewable electricity would improve the environmental performance of salmon farming systems using insect- and algal-based fish feed. Methodological improvements with regard to system C and N cycle, biodiversity, and plastic use should be explored to inform policy making and support the implementation of sustainable future salmon farming innovations.

**Keywords:** life cycle assessment; salmon farming; feed; algal meal; insect meal



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## 1. Introduction

The continuous growth of the global population places increasing pressure on vital resources of food, energy, and water [1]. Seafood constitutes a main source of protein in many countries [2]. In recent years, with many wild fish stocks being exploited at unsustainably high levels, a transition towards fish farming has progressively been taking place [3]. The production of farmed Atlantic salmon (*Salmo salar* L.) reached 2.62 million tonnes globally in 2019, of which Norway produced 1.36 million tonnes [4,5]. Fish farming is responsible for a series of environmental impacts, such as climate change, aquatic eutrophication, and loss of biodiversity due to escapees [2,6].

In this study, an attributional LCA (ACLA) was carried out to (i) estimate the impact on salmon farming of an algal–insect-based diet vs a conventional fish meal/fish oil-based diet, (ii) identify the contribution of each process to the environmental impact of the whole fish farming system, and (iii) identify potential improvements in the algal–insect value chain through sensitivity analysis of various algal–insect production pathways.

This paper is organised in six sections. Section 2 provides a concise review of recent literature on the environmental impacts of aquaculture feed ingredients. Section 3 describes materials and methods, followed by the presentation of results in Section 4. Section 5 discusses the findings and how they relate to other studies. Section 6 concludes the paper.

## 2. Literature Review

The choice of feed ingredients can have significant effects on the environmental impact of salmon farming [7]. Marine feed ingredients are progressively substituted with plant sources, as the rate of aquaculture growth cannot be sustained using fish meal and oil as main dietary ingredients [3,8]. Together with agricultural-based feed sources, insect meal, e.g., from black fly soldier (*Hermetia illucens* L.), has been proposed among protein sources as a valid alternative to fish meal and soybean (*Glycine max (L.) Merr.*), as it does not compete with protein sources for human consumption and is an avenue to generate value from industrial biomass sidestreams and food waste [8,9]. Insect meal has shown to have a better energy transformation efficiency than soybean when considering digestibility and renewability [9]. Recent research also reports an increase in environmental performance of insect meal production from agricultural waste and sidestream biomass [10].

Life cycle assessment (LCA) has been used to assess the environmental sustainability profile of fish farming [11–13], but also of feed ingredients such as agricultural crops, insect production, algal meal, and oil production [8,9,14–16]. Several studies provide recommendations on methodological approaches in life cycle assessment of fish farming [11,13,15]. Others have highlighted the need for LCA to be focused on dietary aspects of fish farming, including changes in the feed conversion ratios (FCR) [2]. Despite the increased interest in alternative fish feed products [7,8,17], no study has so far aimed at assessing a change in fish diet with algal and insect meal using ALCA for salmon farming in Mid-West Norway, considering the feed production implications [2,8,9].

## 3. Materials and Methods

This section describes the experimental cage Atlantic salmon feeding trial and the approach to LCA in 5 sub-sections, dealing with the overall approach, system boundaries, data collection, sensitivity analysis, and the contribution analysis.

### *3.1. Approach, Functional Unit, and Baseline Scenarios*

We carried out a cradle-to-farm gate ALCA. Attributional LCA assesses the existing systems in considerable detail. ALCA has low uncertainties and is well suited for the identification of system improvements [18]. The functional unit is 1 kg of live weight of salmon at the fish farm [11,19,20]. Two different baseline scenarios were considered in this study: (1) cage system with a conventional feed composition (C-C), and (2) cage system with algae–insect-based meal (C-AI). All systems are assumed to be located in the Mid-West Norway region.

The impact assessment method adopted was the product environmental footprint impact assessment framework [21,22] for the following impact categories: climate change with a 100-year horizon, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, resource use (energy carriers; materials and metals), and terrestrial and freshwater acidification. For both the life cycle inventory (LCI) and the life cycle impact assessment, SimaPro software was employed [23].

### *3.2. System Boundary*

The LCA included the phases of salmon farming from the extraction of raw materials used as input in fish farming, fish ingredient production, fish feed processing up to the farming of fish, and all their associated transport and processing. The system boundaries include field cultivation of crop ingredients used in feed and their downstream processing, harvesting of marine ingredients and their associated transport and processing, all salmon farming activities, the production and transport of fuel consumed during farming, as well as the production and transport of other materials used. Figure 1 provides a general description of the system boundary for the two baseline scenarios assessed.

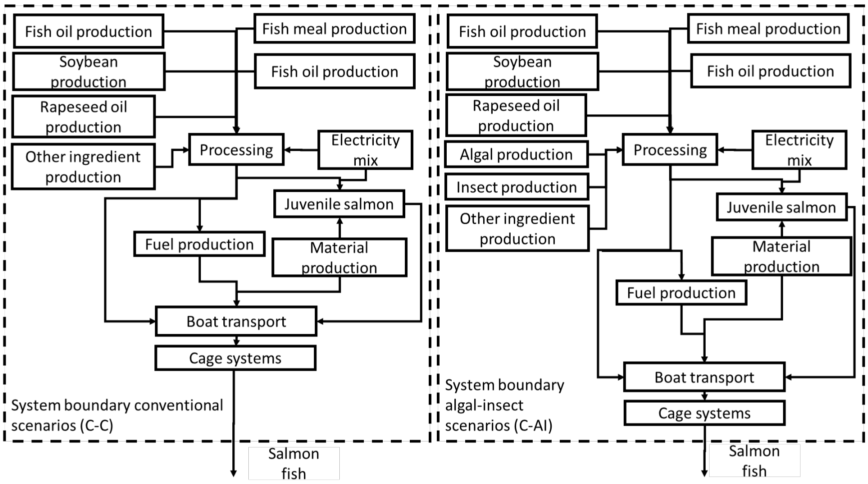


**Figure 1.** System boundaries for C-C (**left**) and C-AI (**right**).

Only the production of materials used in fish farming was considered (following [24]); their assembly was excluded from the system. For cage systems, we only accounted for the operation of the well boat and diesel-fuelled power systems, thus excluding their materials, manufacture, and the anti-fouling paint used for their maintenance. In juvenile production, water consumption was not included in the assessment [24]. Only climate change impact was considered for krill and micronutrient production, excluding phosphorous, due to limited data availability; for other fish ingredients, all the impact categories described in Section 3.1 were accounted for.

### 3.3. Data Sources, Assumptions, and Data Processing

The following sections describe data sources, assumption and data processing for fish farming systems, diets and field experiments, feed production, and processing and analysis of nutrient losses.

#### 3.3.1. Fish Farming Systems

Life cycle inventory data for salmon farming infrastructure, fuel consumption, and the economic feed conversion ratio for juvenile production were taken from [24]. Data contained in [24] are based on a nationwide survey of fisheries and salmon farming facilities in Norway in 2017. Economic conversion ratios for cage farming were measured following the protocol described in the diet and field experiment (see Section 3.3.2). Data for the sea cage systems reported in Table 1 were used in the baseline scenarios and integrated with background processes contained in SimaPro databases [23,25,26]. Table 2 presents a summary of the data sources used for the life cycle inventory.

**Table 1.** Input and waste flows for the cage (C-C; C-AI) and juvenile salmon breeding systems (C-C; C-AI) per functional unit (FU) (1 kg of fresh salmon at farm gate).

| | Unit ($FU^{-1}$) | Conventional Cage System C-C | Algal Insect Cage System (AI) | Juvenile Salmon (C-C; C-AI) | Reference |
|---|---|---|---|---|---|
| **Input flows** | | | | | |
| Juvenile salmon | kg | 0.026 | 0.026 | | [24] |
| Polypropylene | kg | 0.011 | 0.011 | | [24] |
| Polyethylene | kg | 0.011 | 0.011 | | [24] |
| Steel | kg | 0.0045 | 0.0045 | | [24] |
| Chromium steel | kg | 0.0019 | 0.0019 | 0.0286 | [24,27] |
| Feed conversion ratio (FCR) | Kg/kg | 0.89 | 0.96 | 0.9 | Own measurements; [24] |

**Table 1.** *Cont.*

| | Unit ($FU^{-1}$) | Conventional Cage System C-C | Algal Insect Cage System (AI) | Juvenile Salmon (C-C; C-AI) | Reference |
|---|---|---|---|---|---|
| Fuel used in service vessels | L | 0.04 | 0.04 | | [24] |
| Fuel used in power production for the fish farm | L | 0.08 | 0.08 | | [24] |
| Fuel for well boat operations | L | 0.015 | 0.015 | | [24] |
| Farmed lice control fish | kg | 0.0103 | 0.0103 | | [24] |
| Wild-caught lice control fish | kg | 0.0113 | 0.0113 | | [24] |
| Plastic tank used for fish transport [a] | kg | 0.00431 | 0.00431 | | [24] |
| Electricity | kWh | | | 10 | [24,27] |
| Diesel | L | | | 0.033 | [24] |
| Electricity for sludge drying | kWh | | | 0.208 | [24] |
| Oxygen use | kg | | | | [27] |
| Concrete | $dm^3$ | | | 2.33 | [27] |
| Plastic | g | | | 0.0162 | [27] |
| Glass fibre | g | | | 0.0176 | [27] |
| **Waste outputs** | | | | | |
| Steel | g | 6.5 | 6.5 | 0.0286 | [24,27] |
| Plastics [b] | g | 5.81 | 5.81 | | [24] |
| Sewage sludge | kg | | | 0.0015 | [27] |
| Polyethylene waste | g | | | 0.0162 | [27] |
| Concrete waste | g | | | 1.16 | [27] |
| Glass waste | g | | | 0.0176 | [27] |

[a] Based on the assumptions, see Supplementary Materials for details. [b] As sum between data input from [24] (0.0015) and our own calculations to consider the plastic tank used to transport fish; see File S2 SM_LCI for details.

**Table 2.** Summary of the data sources used to carry out the LCA of salmon fish farming.

| | Reference |
|---|---|
| **Fish farming** | |
| Fish farming infrastructure | [24] |
| Fish feed (fish conversion ratio, FCR) | Own measurements (cage farming); [24] (juvenile growth) |
| Smolts farming data | [24,27] |
| Background data related to inputs used in fish farming | [25,26] |
| Biological lice control | [28] |
| **Fish feed processing** | |
| Dietary composition | Fish feed producer |
| Energy and material inputs necessary for the fish processing | Data collected directly from the processing plant |
| Production of fish feed ingredients with the exception of insect meal, algal meal, fish oil and fish meal, krill | [24–26] |
| Fish oil and fish meal | [24–26] |
| Insect meal production | [9] |
| Insect emission during insect production | [29] |
| Algal meal production | [16,30] |
| Krill production | [31] |
| Vitamins, minerals, and amino acids | [24] |
| Other micronutrients | [32] |
| Background data related to inputs used in fish feed processing and ingredient production | [25,26] |
| **Nutrients, C, N, P cycles** | |
| N, P loss, ammonia volatilisation | [11,19,33] |
| Ammonia volatilisation, indirect $N_2O$ emissions | [34] |
| $CO_2$ due to fish respiration | [33] |
| Soil $CO_2$ and $N_2O$ emission due to feed crop cultivation | [34–36] |

Life cycle inventory (LCI) data and assumptions for the cage systems are available in the Supplementary Materials File S2 SM_LCI. Smolt farming was mostly accounted for on the basis of previous publications [24,27]. Lice (*Lepeophtheirus salmonis* Krøyer) treatment data were taken from the literature based on Norwegian conditions [28].

3.3.2. Diet and Field Experiment

A cage trial employing 3953 Atlantic salmon smolts was performed by Nofima in GIFAS (Gildeskål Forskningsstasjon AS) Inndyr, Norway (N 67°, E 14°). The fish were divided in four cages (~1000 fish per cage) and fed two different diets in duplicate: a commercial-like control diet (scenario C-C) and a test diet (scenario C-AI). The trial lasted from 24 October 2019 (start mean fish body weight = 135 g) to 21 August 2020 (end mean fish body weight approx. 1.5 kg). The conventional diet mainly consisted of fish meal, soya protein concentrate (SPC), fish oil, horse beans (*Vicia faba* L.), rapeseed (*Brassica X napus*), and wheat (*Triticum* sp.) products (Table 3). In the C-AI diet, all soybean *(Glycine max (*L.) *Merr.*) protein concentrate, large parts of fish meal, and fish oil present in the control diet were substituted by commercially available black soldier fly (*Hermetia illucens* L.) larvae meal and spray-dried heterotrophic microalgae such as *Schizochytrium limacinum* biomass. Higher levels of wheat gluten were used in the C-AI diet to balance the crude protein levels of the test diet (Table 3).

**Table 3.** Average composition, origin of fish feed ingredients, and details of the LCI for each fish feed type.

| | C-C | C-AI | Origin |
|---|---|---|---|
| **Ingredient** | | | |
| Conventional fish meal | 23.4% | 5.91% | Norway |
| Conventional fish oil | 9.20% | 4.55% | Norway |
| Krill meal/hydrolysate | | 1.01% | Norway |
| Soy protein concentrate | 16.1% | | Brazil |
| Soya/rapeseed lecithin | 1.00% | 1.01% | Germany [a] |
| Rapeseed oil | 15.8% | 16.1% | Denmark |
| Horse beans | 8.20% | 6.94% | France |
| Wheat gluten | 12.7% | 26.3% | 25% Belgium; 75% France [b] |
| Wheat meal | 6.56% | 5.68% | France |
| Algae meal heterotrophic | | 6.75% | Brazil |
| Insect meal | | 17.7% | France |
| Yeast extract | 0.502% | 0.506% | Norway [a] |
| Choline chloride 9/16 | 0.502% | 0.506% | Norway [a] |
| Cholesterol | | 0.34% | Norway [a] |
| Mineral and vitamin mix | 2.56% | 2.58% | Norway [a] |
| Mineral P source | 2.17% | 2.03% | Norway [a] |
| Lysine | 0.612% | 0.894% | Norway [a] |
| Methionine | 0.271% | 0.378% | Norway [a] |
| Threonine | | 0.297% | Norway [a] |
| Histidine | 0.418% | 0.405% | Norway [a] |
| Carop. pink 24/15 | 0.0501% | 0.051% | Norway [a] |
| **Input processing** | | | |
| Electricity consumption (Wh $kg^{-1}$ of fish feed) | 60.9 | 33.2 | |
| Steam (g $kg^{-1}$ of fish feed) | 126 | 82.2 | |
| Water (g $kg^{-1}$ of fish) | 146 | 85.8 | |

[a] Based on assumptions; see File S2 SM_LCI for further details. [b] Based on the assumptions made with data collected from the data provider.

The diets were balanced for crude protein, EPA ± DHA and n-3/n-6 ratio, essential amino acids (Lys, Met, His, and Thr), and soluble P using wheat and horse beans, crystalline amino acids, plant oils, and monosodium phosphate, respectively, to the best of our knowledge based on extensive chemical characterisation of the test raw materials (Table 4).

Feeds were produced in three different pellet sizes used in the trial (4 mm, 5 mm, and 7 mm) at the Aquafeed Technology Center of Nofima in Bergen, Norway (in total approx. 2 tons per diet).

**Table 4.** Chemical composition of experimental diets used in the salmon cage trial. The analytical values belong to the largest pellet size (7 mm) used during the final and longest trial period, representing the largest feed volume consumed (approx. 1800 kg per diet). In the trial, 4 mm (approx. 500 kg per diet, with crude protein and lipid levels of approx. 45% and 25%, respectively) and 5 mm (approx. 840 kg per diet, with crude protein and lipid levels of approx. 42% and 29%, respectively) pellet size diets were used in the initial phase of the experiment.

| | **C-C** | **C-AI** |
|---|---|---|
| Protein % | 37.98 | 37.95 |
| Lipid % | 32.96 | 33.00 |
| Ash % | 5.8 | 4.8 |
| Moisture % | 7.1 | 5.8 |
| Total P % | 1.1 | 1.1 |
| Soluble P % | 0.84 | 0.82 |
| Soluble protein % | 6.31 | 7.40 |
| **Total protein amino acids % in diet** | | |
| Arginine | 2.0 | 1.6 |
| Threonine | 1.5 | 1.6 |
| Valine | 1.7 | 1.6 |
| Methionine | 1.00 | 0.98 |
| Isoleucine | 1.5 | 1.4 |
| Leucine | 2.8 | 2.6 |
| Phenylalanine | 1.8 | 1.8 |
| Lysine | 2.4 | 1.9 |
| Tryptophane | 0.4 | 0.4 |
| Histidine | 1.0 | 1.1 |
| Cystein/cystin | 0.58 | 0.65 |
| Aspartic acid | 3.1 | 2.0 |
| Glutamic acid | 8.4 | 10.4 |
| Hydroksyproline | <0.1 | <0.1 |
| Serine | 1.8 | 1.7 |
| Glycine | 1.7 | 1.6 |
| Alanine | 1.7 | 1.5 |
| Proline | 2.6 | 3.5 |
| Tyrosine | 1.2 | 1.4 |
| Total free amino acids % | 1.76 | 2.47 |
| **Fatty acid profile % in Bligh and Dyer extract** | | |
| 20:4 n-6 | 0.1 | <0.1 |
| 20:5 n-3 (EPA) | 2.6 | 1.1 |
| 22:6 n-3 (DHA) | 3.5 | 4.1 |
| EPA + DHA | 6.1 | 5.2 |
| 16:00 | 7.8 | 10.8 |
| Saturated fatty acids | 12.6 | 14.6 |
| Monounsaturated fatty acids | 51.1 | 44.3 |
| Total identified fatty acids | 90.3 | 84.7 |
| Total unidentified fatty acids | 2.4 | 3.4 |
| Omega 6/omega 3 ratio | 1.01 | 1.28 |
| Total neutral lipids | 89.4 | 84.4 |
| Total polar lipids | 2.7 | 4.5 |

Biological data were subjected to one-way analysis of variance (ANOVA) tests using IBM SPSS statistics 27 to detect dietary effects. When differences between treatments were identified, means were ranked using the Tukey post hoc test. Equality of error variances was tested with Levene's test. Effects were considered at a significance level of $p < 0.05$, and tendencies are discussed at $p < 0.1$.

The cage trial showed that insect meal and microalgae biomass in the C-AI diet have the potential to promote adequate fish growth rates (thermal growth coefficient = 3.1 and FCR = 0.96), but did not reach the performance of fish fed the commercial-like C-C diet (thermal growth coefficient = 3.3 and FCR = 0.89). Atlantic salmon fed the C-C diet grew on average to a final weight (1579 g) that was 204 g higher compared to fish fed the C-AI diet (1374 g) ($p = 0.000$) containing insect meal and *Schizochytrium limacinum* biomass replacing fish meal and fish oil, respectively. There was a tendency for higher final body weight, TGC (thermal growth coefficient), and survival ($0.1 < p < 0.05$) in the control treatment, whereas the differences in SGR (specific growth rate) were statistically significant ($p < 0.05$) and in favour of the control diet. The growth rate differences were, however, rather small, and the FCR values were adequate in both treatments. During the trial, fish suffered mortality due to winter sores caused by *Moritella viscosa (Lunder) Benediktsdóttir* and *Tenacibaculum maritimum (Hikida) Yoon* and an outbreak of HSMI (hearth and skeletal muscle inflammation). Higher mortality rates were seen in the C-AI treatment compared to the control (C-C), and though the difference in mortality rate was not statistically significant ($0.1 < p < 0.05$), it contributed to the difference in the FCR between the two treatments. Fish in the C-AI treatment had a significantly lower condition factor as compared to the C-C control ($p < 0.05$), which is expected and consistent with the fact that they had also lower body weight. The analysis of the reasons behind the observed dietary effects is beyond the scope of this paper.

#### 3.3.3. Feed Production and Processing

LCI of feed composition is provided in File S2 SM_LCI. It was assumed that all the ingredients were transported 10 km from the harbour before reaching the feed processing facility, located in Bergen, Norway.

LCI for each ingredient was taken from databases contained in SimaPro software [25,26,37] and Agribalyse [38], except for fish meal, microalgal biomass meal, insect meal, and micronutrients. Specific names of processes are reported in File S2 SM_LCI. The dietary fish meal composition was taken from [24]. Data for fish meal processing were taken from databases contained in [25,26,37], and fish feed processing data were obtained directly from the producer (Table 3). The LCI for the herring fish production, sprat, and purse seine fishing are available in the File S2 SM_LCI.

The main assumptions regarding transport are described in File S2 SM_LCI. Data for wheat flour production were used in place of wheat meal. The insect meal processing data were accounted for according to the literature [9]. Following the approach taken in [16,39], physical allocation based on mass output was utilised to assess the impact of insect meal and insect fat. The respective transport assumptions are described in File S2 SM_LCI. The *Schizochytrium limacinum* meal data used were based on the heterotrophically produced algal biomass from an optimised facility using sugarcane (*Saccharum officinarum* L.) sugar in Brazil by [30]. LCI for algal biomass was then adapted to account for transport considering the Brazilian production facility following the assumptions shown in File S2 SM_LCI and assumptions made by [30]. Data for krill production were sourced from the literature [31], and it was assumed that krill were landed directly in the harbour of Bergen, Norway.

As there were limited data available for micronutrients in the literature (Bohnes et al., 2018), micronutrients added to the fish feed were distinguished in four categories: vitamins and minerals, phosphorous accounted as phosphate, amino acids, and other micronutrients (including pigments and cholesterol). For vitamins, minerals, and amino acids in fish feed, data reported in [24] were used. Phosphate data on phosphate fertiliser production information were sourced among the processes present in [26], while for the other micronutrients, climate change data from [32] were used.

#### 3.3.4. Nutrient Loss, C, N, and P Cycles

The treatment of nutrient loss in cage systems follows that of [11,19] and is calculated as a difference between nutrients contained in the feed and nutrient uptake for both N and P by the salmon farmed. N and P contents of the salmon tissue were taken from the literature [33], while ammonia emissions were calculated in line with the Intergovernmental Panel on Climate Change on the basis of fish feed N content [36], as carried out in previous research studies [40]. Carbon dioxide production due to salmon respiration was accounted for in both cases using data from the literature based on the carbon content of the feed [40]. It was assumed that 40% of the C contained in the feed was lost as $CO_2$ during respiration, all N was released as ammonia, and P was released as phosphate due to anaerobic conditions in the water [33,41]. Indirect $N_2O$ emissions due to ammonia volatilisation from fish farming were accounted for by adopting the most recent Intergovernmental Panel for Climate Change (IPCC) methodology [34].

For each crop-based ingredient in the fish meal, IPCC Tier 1 emissions factors were used to account for C dynamics and $N_2O$ emissions due to the soil organic matter degradation related to land management practices, in line with [34–36]. This methodological choice was taken considering the objectives of the assessment and the available data [39,42–44]. GHG emissions of land management related to sugarcane production were not accounted for, as land management data were not available from the heterotrophic algal production sources [30]. Further details are provided in File S1 SM_GHG. Emissions during insect production were taken from previous works, assuming the same emission value for all insect-growing media [29], due to limited data availability.

### *3.4. Sensitivity Analysis*

A sensitivity analysis was undertaken to analyse changes in the environmental performance under the following scenarios. Scenarios were formulated together with local partners, considering data availability and the ongoing work on innovative technologies and potential new strategies to increase efficiency in the utilisation of inputs and potential reutilisation of sidestream biomass sources [3,9,10,30]. The influence of 10% variation in the fish to feed ratio was examined (10% F sensitivity scenario). Further details on the sensitivity analysis scenario are provided in the File S2 SM_LCI supporting information file. An alternative transport sensitivity scenario for fish feed transport in the Norwegian context was also assessed, assuming a 1000 km distance (i.e., the 1000 km sensitivity scenario).

Other specific sensitivity scenarios were tested for C-AI, as it was reported that different efficiency levels could be achieved depending on the raw materials and energy input [9,10]. In the NEFF scenario, the autotrophic algae were produced from glucose available on the market in the U.S. using data from [16]. In the Algal Renewable Energy Exhaust Heat AREH scenario, it was considered that all the electrical energy used in algal feed production is produced from photovoltaic renewable systems and the heat necessary throughout the process was exhaust heat in the same U.S. location as in the NEFF scenario and the same algal production facility (File S2 SM_LCI).

In the Insect Exhaust Heat (IEH) scenario, the heat necessary in the insect production was assumed to be exhaust heat (for further information, see File S2 SM_LCI), while algal biomass was coming from the same facility as in the AI baseline scenario with data from the literature [30]. In the DDGS scenario, it was considered that the insect meal was produced at distilled dry grains (DDGS) in France and algae were from the Brazil facility [30], as in the baseline AI scenario. In the Norway (NO) sensitivity scenario, it was assumed that both the insect and algal production facilities are located in Bergen, 10 km away from the fish processing facility, with the same characteristics as in [16,45], while the insect meal agricultural inputs came from The Netherlands and microalgae were made from glucose (File S2 SM_LCI). For both NO and DDGS sensitivity analysis scenarios, the same methodological approach described in the SI_GHG supporting information file was adopted to account for soil management due to the production of the agricultural inputs necessary for insect meal production. All these sensitivity scenarios were compared to the baseline (B) for the two scenarios analysed (C-C and C-AI) using the inventory data and assumptions presented above and in the File S2 SM_LCI.

For reasons of clarity, Table 5 provides a summary of scenarios assessed.

**Table 5.** Nomenclature of scenarios.

| Scenario Shorthand | Full Name |
|---|---|
| C-C | Cage system with conventional feed composition |
| C-AI | Cage system with algae–insect-based meal |
| 10% F | The influence of 10% variation in fish to feed ratio |
| 1000 km | An alternative transport sensitivity scenario for fish feed transport within the Norwegian context was also assessed, assuming 1000 km distance data |
| NEFF | The autotrophic algae were produced from glucose available on the market in U.S. |
| AREH | All the electrical energy used in algal feed production is produced from photovoltaic renewable systems |
| IEH | Heat necessary in the insect production was assumed to be exhaust heat |
| DDGS | Insect meal was produced from distilled dry grains (DDGS) in France |
| NO | Both the insect and algal production facilities are located in Bergen, 10 km away from the fish processing facility |

### *3.5. Contribution Analysis and Data Processing*

A contribution analysis was carried out, in line with the ISO standard for LCA [39,43], to identify key processes that contribute most to the overall environmental impact of the fish farming systems assessed. Under the fishing boat category, the impacts related to the fishing boat, well boat, and transport boat use were grouped together. Data processing was carried out using both SimaPro and R [23,46].

## 4. Results

Results are presented in three sub-sections: absolute results, contribution analysis, and sensitivity analysis.

### *4.1. Absolute Results*

The results of the ACLA are presented in Figure 2 for seven impact categories. Each graph presents findings for one impact category, both the C-C scenario (left-hand side of the graph) and the C-AI scenario (right-hand side of the graph). Graphs present absolute numbers, and the following paragraph includes data on the relative differences between C-C and C-AI.

The baseline C-C scenario obtained a lower impact than the C-AI system for all impact categories analysed (51.5% on average). The largest difference between the C-C and C-AI systems was observed for marine eutrophication (79.9%), while the lowest variation was obtained for freshwater eutrophication (9.6%) (Figure 2).

Resource use for energy carriers resulted in a greater gap between C-C and C-AI scenarios (57.3%) than climate change (35.8%). Besides the environmental impacts of the various diet ingredients, the diet largely affected the fish farming performance (C-C diet FCR 0.89, C-AI 0.96, Table 1), thus influencing the overall environmental impacts of the two baseline scenarios (C-C and C-AI) (Figure 2).

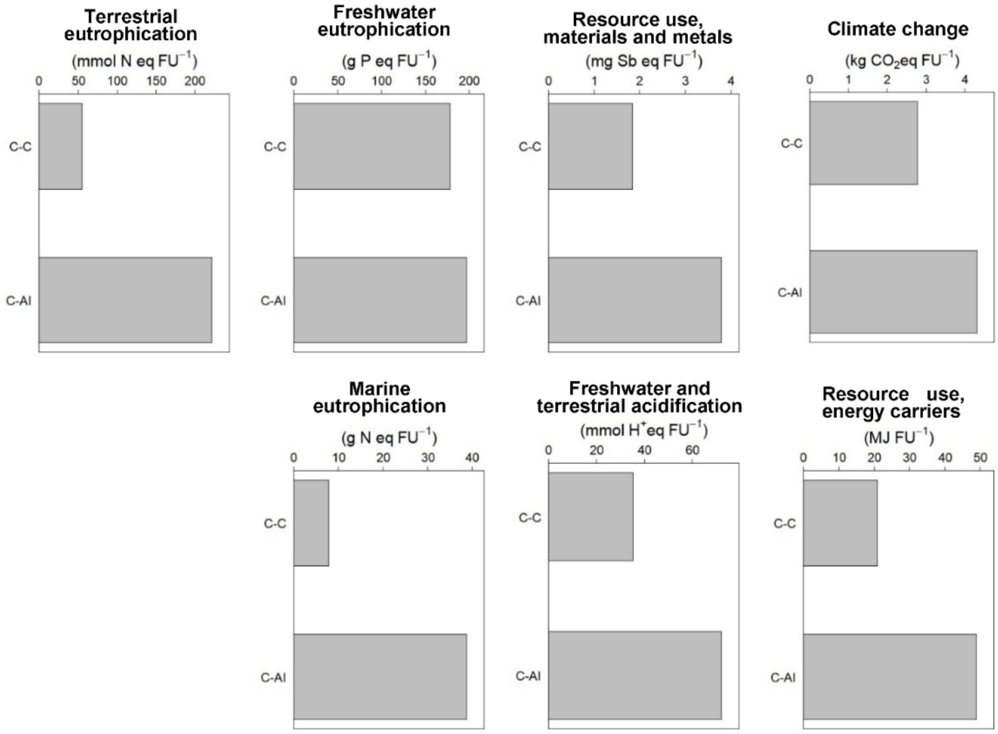


**Figure 2.** Visualisation of absolute results per impact category.

### *4.2. Contribution Analysis*

The fish feed composition highly affected the contribution of various processes to the impact analysed in this study (see Table 6). Fish farming processes excluding fuel consumption due to fish transport, well boats, and diesel-powered systems and juvenile salmon production resulted in the highest contribution on average across the various environmental impacts considered (18.8% on average), followed by other processes in fish feed production (10.8%). For the C-C scenario, the largest contribution to the environmental impacts analysed was observed for other processes in fish farming (20.6% on average); for the C-AI baseline scenario, the largest contribution was from rye (*Secale cereale* L.) middlings (42.7% on average) (Table 6).

**Table 6.** Contribution analysis in % for the two analysed baseline scenarios (C-C, C-AI) in ALCA expressed in percentage over the total impact from cradle-to-gate of cage fish farming.

| | | **Fish Farming** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Fish Feed Production** | | | | | | | | | |
| | | | | | | | | | | | | | **Insect Production** | |
| **Impact Category** | **System** | **Fishing boat [a]** | **Juvenile salmon production** | **Other processes [b]** | **Fish meal production** | **Fish oil production** | **Soybean protein concentrate production** | **Rapeseed oil production** | **Wheat gluten production** | **Amino acid production** | **Other processes [c]** | **Algae production** | **Rye middling production [d]** | **Other processes [d]** |
| Climate change | C | 22.8 | 1.7 | 7.2 | 6.1 | 3.7 | 31.2 | 6.2 | 2.9 | 6.0 | 12.2 | 0 | 0 | 0 |
| | AI | 14.7 | 1.1 | 4.6 | 1.1 | 1.3 | 0 | 4.4 | 4.1 | 5.7 | 9.3 | 1.7 | 46.4 | 5.7 |
| Resource use—energy carriers | C | 27.6 | 1.1 | 20.3 | 8.6 | 6.2 | 12.7 | 5 | 5.4 | 0 | 13.2 | 0 | 0 | 0 |
| | AI | 11.8 | 0.5 | 8.7 | 1.0 | 1.4 | 0 | 2.3 | 5.2 | 0 | 6.2 | 1.1 | 42.7 | 19.1 |
| Resource use—minerals and metals | C | 4.1 | 4.0 | 4.3 | 47.2 | 5.8 | 2.7 | 1.4 | 0.6 | 0 | 30.0 | 0 | 0 | 0 |
| | AI | 2.0 | 1.9 | 2.1 | 6.2 | 1.5 | 0 | 0.7 | 0.6 | 0 | 20.1 | 48.9 | 12.5 | 3.5 |
| Freshwater and terrestrial acidification | C | 25.4 | 37.2 | 2.9 | 7.7 | 1.7 | 3.6 | 11.6 | 2.3 | 0 | 7.5 | 0 | 0 | 0 |
| | AI | 12.4 | 18.2 | 1.4 | 1.0 | 0.5 | 0 | 6.2 | 2.5 | 0 | 3.7 | 1.4 | 50.4 | 2.2 |
| Freshwater eutrophication | C | <0.1 | 0.1 | 99.7 | <0.1 | <0.1 | 0.1 | <0.1 | <0.1 | 0 | <0.1 | 0 | 0 | 0 |
| | AI | <0.1 | 0.1 | 99.6 | <0.1 | <0.1 | | <0.1 | <0.1 | 0 | <0.1 | <0.1 | 0.2 | <0.1 |
| Marine eutrophication | C | 1.1 | 0.3 | 3.9 | 6.7 | 3.5 | 14.3 | 38.9 | 9.7 | 0 | 21.6 | 0 | 0 | 0 |
| | AI | 0.2 | 0.1 | 0.8 | 0.4 | 0.4 | 0 | 8.6 | 4.4 | 0 | 5.6 | 2.0 | 74.4 | 3.1 |
| Terrestrial eutrophication | C | 10.1 | 2.9 | 5.9 | 10.4 | 5.3 | 8.6 | 32.8 | 6.4 | 0 | 17.7 | 0 | 0 | 0 |
| | AI | 2.5 | 0.7 | 1.5 | 0.7 | 0.7 | 0 | 9.0 | 3.5 | 0 | 4.6 | 1.5 | 72.6 | 2.7 |

[a] This category includes all the impacts related to fishing boat, well boat, and transport boat use during fish farming. [b] Other processes that are part of the fish farming phase, excluding those present in the table. [c] Other processes that are part of the fish feed production, excluding those present in the table. [d] Processes necessary for insect production; "other processes" correspond to the processes involved in insect production, excluding rye middling production, which is already present in the table.

In the conventional feed scenario (C-C), most of the climate change impact was due to soybean protein concentrate production (31.2%), while for the algal–insect baseline scenario, the highest contribution was observed for the rye middling production, used as input in the insect meal production (46.4%). In the C-C system, the use of fuel for the fishing and well boats was responsible for up to 22.8% of the climate change impact, followed by other processes in fish feed production (12.2%). Other minor contributions to climate change were obtained for rapeseed oil production (6.2%) and amino acid production (6.0%). For the C-AI scenario, the use of fishing boats and diesel-fuelled power systems was responsible for 14.7% of the climate change impact, while other processes in fish feed processing contributed less to climate change (9.3%) (Table 6).

The impact of resource use for energy carriers was affected by the fuel use for the well boat, fish farming transport, and diesel-powered fish farming system for the C-C scenario (27.6%); in the C-AI scenario, the impact was affected by the rye middling production (42.7%). In the case of the C-C scenario, the impacts of resource use for energy carriers were due to other processes in fish farming (20.3%), other processes in fish feed production (13.2%), and soybean concentrate production (12.7%). In C-AI systems, insect production processes other than rye middling production and the fuel use for the well boat, fish farming transport, and diesel-powered fish farming systems also had relevant impacts (19.1–11.8%). The impact of resource use for materials and metals was largely caused by fish meal production (47.2%) in the C-C scenario and algal production in the C-AI scenario (48.9%); other processes had less important contributions (<12.5%), with the exception of other processes in fish feed production (20.1–30.0%) and rye middling production in the AI system (12.5%) (Figure 2).

Marine and terrestrial eutrophication impacts were mostly caused by rapeseed oil production in the C-C scenario (32.8–38.9%) and by the rye middling production in the AI scenario (72.6–74.4%). In the C-C system, other processes in fish feed production (17.7–21.6%) also contributed to both terrestrial and marine eutrophication impacts. For both baseline scenarios, freshwater eutrophication was mostly due to other processes in fish farming including nutrient discharges into the water (>99.6%) (Table 6).

### *4.3. Sensitivity Analysis*

The results of the sensitivity analysis are presented in Figure 3 per impact category for all scenarios. Scenarios based on C-C are presented in blue and scenarios based on C-AI in green. The results show that together with the fish feed ingredient composition, the technology and input sources for algal production—in particular, the origin of the sugar employed for autotrophic algal growth—are major factors affecting the overall impact for all impact categories assessed, with the exception of freshwater and terrestrial eutrophication for the C-AI scenarios. For instance, at least a 27.2% larger impact was obtained on average across environmental impact categories analysed for the NO, NEFF, and AREH scenarios with regard to the baseline AI scenario (Figure 3). In these scenarios, glucose available on the market was used to produce microalgae in place of sugarcane sugar, as in the baseline AI scenario. In contrast, the increase in feed consumption was responsible for up to 11.8% on average across the environmental impacts analysed (Figure 3).

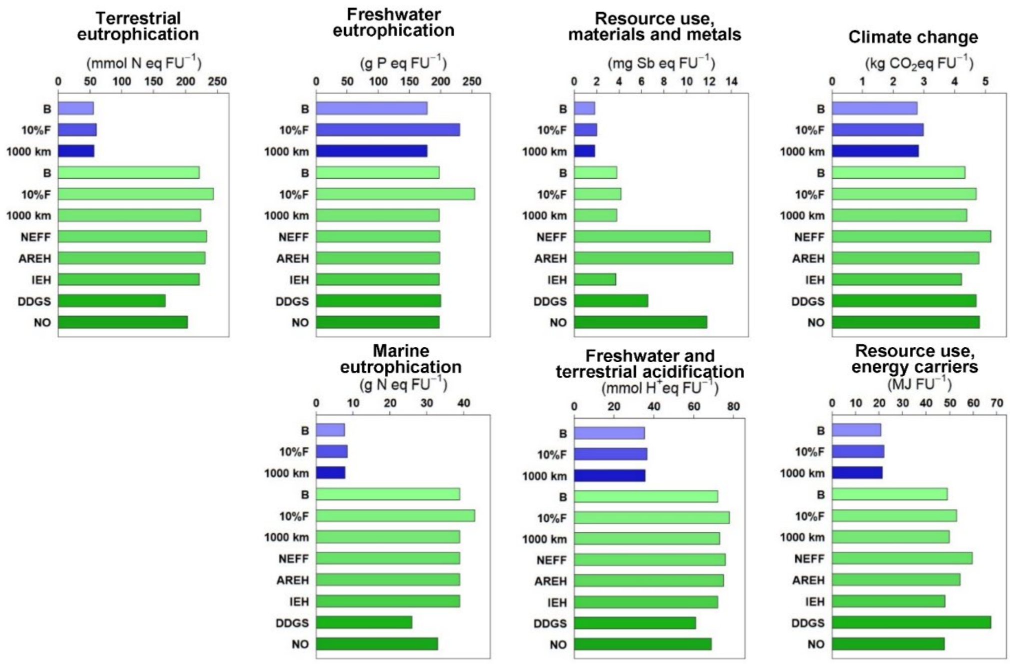


**Figure 3.** Results of the sensitivity analysis, presented per impact category, for all scenarios. Scenarios based on C-C are presented in blue; scenarios based on C-AI are in green.

The largest difference with regard to the baseline climate change was observed for the NEFF scenario (17.4% increase from the B-AI scenario), while for the C-C scenarios, the largest change was obtained with an increase in feed consumption (7.0%). In the sensitivity scenarios for the algae–insect-based feed (NEFF, AREH, IEH, DDGS, NO), less variation was obtained for the NO scenario (11.1%), the AREH scenario (10.6%), and DDGS (8.4%) (Figure 3).

The resource use for energy carriers was largely increased in the DDGS (37.5%), NEFF (19.4%), and AREH (11%) scenarios and was subject to a relevant reduction in the NO (2.5%) and IEH (2.1%) scenarios for the C-AI system. For the C-C system, the 10% F scenario also caused a 5.2% increase in resource use impact for energy carriers. Regarding the resource use impact for materials and metals in the AI scenarios, the greater variation was found in

AREH (2.7-fold larger impact than baseline), NEFF (2.2-fold larger impact), and NO (2.1-fold larger impact). In contrast, more limited changes were observed for the C-C scenario (<8.9%) for the same impact. Freshwater and terrestrial acidification impacts were lower with DDGS (15.9% decrease), NO (4.8% reduction), and IEH SA scenarios (0.1% decrease) than the baseline AI scenario. The other SA scenarios both for AI and C-C resulted in a more limited impact increase (<7.1%) (Figure 3).

For the 10% F SA scenario in both C-C and AI systems, the freshwater, marine, and terrestrial eutrophication increased up to 29%. In contrast, for DDGS and NO SA scenarios, a reduction in eutrophication impacts was obtained for marine and terrestrial eutrophication (up to 32.4%). For freshwater eutrophication in DDGS and NO SA scenarios and for all the other SA scenarios (i.e., 1000 km in C-C and AI; NEFF; AREH and IEH), more limited variation in eutrophication impacts was obtained (<4.0%) (Figure 3).

## 5. Discussion

In this section, we discuss the results of ACLA, relating them to other studies, and outline options to reduce environmental impacts.

### *5.1. Overall Results in Comparison to Other Studies*

Climate change impacts for the baseline C-AI scenarios were close to the average value suggested by [3] (4.4 kg of $CO_2$eq kg$^{-1}$ of fish live weight) in their review of fish farming systems and within the range found in a survey of Norwegian salmon farms, as reported in [24]. The baseline C-C scenario results are 36.8% lower than the value proposed by [3] and 15.8% lower than the range reported in [24], using a different diet composition [24]. The resource use impact for energy carriers (20.9–49 MJ kg$^{-1}$ of live weight of salmon at the fish farm) was within the range of the cumulative energy demand values reported by several research reviews regarding salmonid fish farming [3,28] (0–350 MJ kg$^{-1}$ of fish live weight).

The terrestrial and freshwater acidification potential obtained in our study (35.4 mmol H + eq. FU-1) for the C-C system agreed with the corresponding acidification potentials reported for salmonids in recent reviews with different impact assessment methods (13.1–328 mmol H + eq. FU-1) [3,28]. The C-AI system (72.4 mmol H + eq FU-1) acidification potential was larger than the corresponding values reported by [28] (>52.4 mmol H + FU-1) but in line with Ref. [2] figures calculated with different impact assessment methods (19.7–328 mmol H + FU-1).

The freshwater eutrophication impacts obtained in our study (178–197 g P FU-1) were within the range of corresponding values reported by [3] with different impact assessment methods (<330 g P FU-1) for eutrophication, but larger than the corresponding potentials reported by [28] for salmonids with different impact assessment methods (>27.7 g P FU-1). These differences can be explained by the various methodologies adopted to account for N and P, as discussed by several researchers [44,47].

### *5.2. Fish Feed Ingredients*

This study confirmed that fish feed production is the main contributor to several environmental impacts of aquaculture, including climate change, resource use (energy carriers; minerals and metals), and marine and terrestrial eutrophication (34.4–98.9%). For climate change, 68.3% to 79.7% of the total impact was related to fish feed production in this study based on the ALCA (the percentages reported here correspond to the sum of all the processes related to fish feed production, excluding fish farming processes, present in Table 6), while contributions of around 83.8–93% (sum of fish farming processes, excluding fish feed process) to the overall climate change impact have been reported for fish farming in several locations worldwide [17,44,47,48]. This difference can be attributed to the low feed-to-fish conversion ratios (<0.96) used in this study.

Previous works reported that most of the eutrophication potential is due to nutrient loss from uneaten feed and metabolites of salmon growth during farming [2,17,44,47], which is consistent with the results obtained here for freshwater eutrophication in the other processes that are part of fish farming (>99.6%), including nutrient loss for both cage systems (C-C and C-AI).

The use of marine ingredients resulted in a lower contribution (<15.7%) to most of the impact categories assessed according to results, in line with previous LCA research [44,47,49,50]. However, the present LCA excludes impacts on marine biodiversity [2,51]. For resource use of minerals and metals, the impact of fish meal production was related to the antifouling agents used in fish boat maintenance for wild-caught fish production. The use of antifouling agents largely affects the impact of resource use for minerals and metals, as reported by [48]. Soybean protein concentrate had a high contribution (12.7–31.2%) to climate change, resource use for energy carriers, and marine eutrophication for the conventional feed system (C-C), as previously discussed [17,44]. Nevertheless, in our study, we assumed that soybean protein concentrate was produced in Brazil; European soybean might result in a different environmental profile, as crop environmental performance is highly affected by local conditions [14,52]. Together with soybean protein concentrate, rapeseed oil production had a large contribution (<38.9%) in most of the impact categories assessed here, as reported in previous research [44].

Insect meal and *Schizochytrium limacinum* production contributed up to 79.5% (corresponding to the maximum contribution sum across the impact categories analysed) across all impact categories assessed in the C-AI baseline scenario. Therefore, the shift towards non-marine ingredients should be undertaken, avoiding environmental trade-offs between different fish feed sources (e.g., fish meal vs soybean protein concentrate vs insect meal) and environmental impacts (climate change vs biodiversity) [2,49]. A careful choice of non-marine ingredients should be considered using an LCA approach prior to adoption to minimise the environmental impact of fish feed production [2,17]. Furthermore, there may be new fish feed ingredients that can substitute less sustainable options, such as those proposed by [53,54], including bacterial and fungal proteins and earthworms, even though there are now regulatory restrictions on fish feed sources [55].

Previous studies concluded that a decrease in the feed-to-fish conversion ratio would greatly reduce the environmental impacts and reduce costs [2]. Here, this has also been observed in sensitivity analysis scenarios (10% F), where a 10% increase in feed consumption corresponded to a 10.2–11.8% larger impact on average across environmental impact categories analysed for both baseline scenarios.

### *5.3. Logistics and Technology in Algal and Insect Meal Production*

Several research studies highlight the need for further technological development to increase process performance and reduce environmental impacts, combined with further LCA assessment [47,53,54,56]. The results obtained here for the sensitivity analysis showed a large variability among the sensitivity scenarios based on the AI systems; the contribution analysis showed that the input used to produce the insect meal, rye middling, resulted in a 42.7% average contribution towards the impacts analysed. Furthermore, the input used to produce the microalgae is particularly important. As the sensitivity analysis showed, a change towards a more optimised sugarcane sugar-based algal production led to an average decrease in the environmental impacts of 12.3% for the baseline AI scenario in comparison to the glucose-based algal production SA scenario (i.e., NEFF, AREH, and NO; SM_LCI), as previously discussed [30].

Other factors including the reuse of exhaust heat in algal production, renewable electricity use, and the location of the insect meal and algal production facilities largely affected the overall algal–insect system impact. This outcome was also influenced by the characteristics of the Norwegian electricity grid, highly reliant on renewable and hydroelectric energy [57], and by decreasing transport impacts. This agrees with recent findings related to insect meal production using exhaust heat and biomass energy [10]. Furthermore, the use of different biomass sources, such as DDGS, for insect meal production caused environmental trade-offs among the environmental impacts assessed for the AI system.

Algal production and insect meal production technologies are emerging technological solutions [9,16]. Thus, the present results and variability shown in the sensitivity analysis clearly highlight that these technological pathways could be improved to increase the environmental performance, which highly affects the fish farming performance, as reported in recent research [10,58,59]. This highlights the need to optimise the production chain for these new feed ingredients [2].

For insect meal production, the environmental impact could be improved through a careful choice of the biomass input stream, an optimised use of exhaust heat [9,10], and a careful selection of electricity sources, as previously discussed for salmon farming [50]. However, as for most new technologies, there is a need for transparency and high data quality to carry out assessments to properly inform decision making [2,59].

### *5.4. Methodological Issues*

We carried out an ALCA of several impacts using the product environmental footprint impact assessment methods [21,22]. We acknowledge the limitations of not assessing plastic pollution, biodiversity impacts, toxicity of pesticide residues, and the impact of fish escape, all of which have been highlighted as important aspects in the LCA of fish farming, as previously discussed [60,61]. Further LCA methodology improvements are necessary to properly characterise these impacts [51,60]. However, there is no general approach to account for biodiversity in LCA, as highlighted by [51]. Additional insight could have been acquired with a Consequential Life Cycle Assessment (CLCA) to understand complex changes in the environmental footprint of the food system. However, this might lead to further uncertainties, as previously discussed [13,18,62].

The results obtained showed that switching from a fish-based diet to an algal–insect diet can cause higher environmental impacts and trade-offs. This could include decreasing terrestrial biodiversity by putting more pressure on crop cultivation and increasing demand for agricultural products. Thus, comparing biodiversity impacts of marine and plant ingredients is often difficult, as previously discussed [44].

The present research aimed to address emissions in the environment of ammonia, P, and nitrous oxide due to fish metabolism and uneaten feed, and carbon dioxide from respiration. The method adopted for cage systems followed that of [11,19]. In the marine environment, nitrous oxide can be released into the water [63], and therefore, further methodological development is necessary to assess the amount of nitrous oxide released into the water column, which can be emitted to the atmosphere in cage systems.

Regarding data quality, the data in this study were mostly sourced from national surveys and reports assessing the salmon farming sector in Norway [2,64], as specific data from companies were not available for confidentiality reasons. Furthermore, [2]'s data are based on one year of data (2017), and technological development and seasonal variability could affect the overall fish farming performance [9,16,53]. Diet data were gathered directly from the producers, considered a key parameter for the LCA of fish farming [3]. However, it is possible for the same ingredient to be made using different technologies and having different environmental profiles [9,10,30]. This could lead to further uncertainties in the LCA, as available data are limited for new technologies [59].

This study also disclosed all the foreground processes in line with the need for transparency, suggested by previous research [2,65–73]. However, specific data on new fish feed ingredients are often considered commercial secrets by companies producing fish ingredients [30], which only partially present the input data used in their assessment. In this research, the issue was partially overcome by taking data from previous publications [9,16,30]. Finally, data for micronutrients were taken from a few available sources [24,32]. Nevertheless, better data quality should be achieved with these feed components by undertaking a specific LCA for each micronutrient, as they can have a large contribution to the overall feed impact.

## 6. Conclusions

We aimed to compare two salmon diets in cage farming systems. A change in fish feed composition from marine ingredients towards an insect–algal-based fish feed composition resulted in higher environmental impact for most environmental impact categories assessed. However, the overall performance of the system was largely affected by the production pathways and input used in algal and insect meal production, together with other ingredients such as soybean protein concentrate and rapeseed oil. Improving production pathways of feed ingredients largely reduces the environmental impact of salmon farming. This includes optimising production pathways for ingredient production by using inputs for feed ingredient production with less environmental impact, locating the feed ingredient production close to the fish feed production facility, and by using food by-products, exhaust heat, and renewable energy to produce fish feed ingredients. Increasing the overall economic feed-to-fish conversion ratio also largely decreases the environmental impact of fish farming. Further methodological improvement with regard to C and N cycle, biodiversity, plastics, and escapees should be explored to expand the range of environmental impacts assessed in LCA. This can support decision makers and fish farming innovators in the development of low-impact aquaculture practices that allow the production of seafood at low environmental costs.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su141912650/s1: File S1: SM_GHG.xlsx (the calculation sheet for soil greenhouse gases due to land management for the crop cultivation of fish feed ingredients) and File S2: SM_LCI.xlsx (life cycle inventory for each of the main process described in the text present in the C, AI, and sensitivity scenarios).

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**Institutional Review Board Statement:** The described procedures are not within the scope of the Regulation concerning the use of animals for scientific purposes. In accordance with Norwegian and European legislation related to animal research, formal approval of the experimental protocol by the Norwegian Animal Research Authority (NARA) is not required if the experimental conditions are practices undertaken for the purpose of recognized animal husbandry. Such practices are excepted from the European Directive on the protection of animals used for scientific purposes (2010/63/EU), cf. article 5d.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data is provided as Supplementary Materials.

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