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Water scarcity- and carbon footprints of aquafeed: The case of land-based and ocean-based Atlantic salmon (*Salmo salar*) farming in Iceland

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ABSTRACT

The water scarcity footprint (WSF), carbon footprint, and blue and green water footprints accounting of the aquafeed used in land-based and ocean-based Atlantic salmon (*Salmo salar*) farming in Iceland in the year 2021 were assessed through a cradle-to-processor-gate attributional Life Cycle Assessment (LCA) study. The main research questions were: 1) What aquafeed ingredients are environmental hotspots? 2) How does the country of origin of certain aquafeed ingredients affect their environmental performance? 3) Are there any environmental trade-offs between WSF and the carbon footprint of aquafeed ingredients production? All plant ingredients of the aquafeed for salmon farming in Iceland are sourced from abroad, making the sector vulnerable to disruptions within the supply chain, dependent on other countries' natural resources, and responsible for the contributions put on the local water resources of producing countries. The major WSF contributors were maize meal (for land-based salmon farming) and wheat gluten (for ocean-based salmon farming), which were largely sourced from China. Rainwater (green water) is the largest source of irrigation for all plant-based aquafeed ingredients, which could potentially be depriving natural ecosystems of rainwater if land is transformed for agriculture. The carbon footprint of the aquafeed for the land-based and ocean-based salmon farming was largely explained by soybean meal sourced from Brazil, due to the high land-use changes. Future efforts to reduce water use and carbon emissions should be focused on sourcing aquafeed ingredients based on their lowest water and carbon footprints, as well as with national food security aspects in mind.

1. Introduction

In the latest Food and Agriculture Organization (FAO) fisheries report, sustainable aquaculture has been reported as a key element in reducing food insecurity without compromising the well-being of the environment (FAO, 2022). Iceland is privileged with its geographical location, which allows for natural access to abundant water (fresh, brackish, and seawater) for land-based aquaculture. In addition, Iceland is surrounded by warmer ocean temperatures for ocean-based aquaculture, compared to other places with such closeness to the Artic Circle due to the Gulf stream, and its branch, the Irminger current (Casanova-Masjoan et al., 2020). Moreover, Iceland possesses easy access to- and use of- renewable energy from green sources such as hydropower and geothermal energy (Government of Iceland, 2024). These traits facilitate the development of salmon farming both on land and in the ocean. Iceland farmed 46,458 tonnes of Atlantic salmon (*Salmo salar*) in 2021, of which 96 % of the production was ocean-based, and 4 % was land-based (Statistics Iceland, 2024). Sea farms are mainly in the West and East fjords, while land-based farms are largely in the north and south of the country (MAST, 2024). Eighty-six percent of the country's salmon farmed on land is operated by a single company, while the ocean-farm operations are mainly owned by three large companies, which have majority owners from Norway. These companies are Ice Fish Farms, Artic Fish, and Arnarlax/Icelandic Salmon, and they account for 41 %, 27 %, and 26 % of the market share, respectively (Government of Iceland 2023). The number of salmon currently farmed in Icelandic waters was sufficient to meet the domestic demand, and the surplus

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Nomenclature

AMD Availability minus demand
AWARE Available Water Remaining. Metric(s) that quantifies the potential environmental impacts related to freshwater consumption (Boulay et al., 2018)
Blue water availability river and groundwater available after environmental requirements have been met (Hoekstra et al., 2009)
Blue water footprint Volume of surface and groundwater consumed as a result of the production of a product or service (Hoekstra et al., 2009)
Blue water Ground or surface water, including rainwater that is not absorbed by the soil and ends up in lakes, ponds, rivers, aquifers, and oceans (Hoekstra et al., 2009)
Brackish water water with salinity levels between 1000 and 30,000 mg/L (ISO, 2014)
CF Characterization factors
Exogenous water Imported virtual water.
FCR Feed Conversion Ratio
FMFO Fishmeal and Fish Oil
Freshwater Water with less than 1000 mg/L of dissolved salts (ISO, 2014)
FU Functional Unit
GHGs Greenhouse Gases
Green water footprint volume of green water consumed during the production process (Hoekstra et al., 2009)
Green water Rainwater that does not run off or recharge the groundwater but is stored in the soil or temporarily stays on top of the soil or vegetation (Hoekstra et al., 2009)
Grey water Water needed to dilute pollutants to an extent that the quality of the water remains above agreed water quality standards (Hoekstra et al., 2009)
GWP Global Warming Potential (kg CO_2 equivalents)
Indigenous water water found within a nation's territory (Hoekstra, 2003)
LCA Life Cycle Assessment
Seawater Water with salinity levels above 30,000 mg/L (ISO, 2014)
Virtual water Water needed to produce an ingredient that becomes embodied in the product (Hoekstra, 2003)
WF Water Footprint
WFA Water Footprint Assessment
WFN Water Footprint Network
WSF Water Scarcity Footprint
WSI Water Scarcity Index

(roughly 32 thousand tonnes in 2021, valued at 200 million EUR) was exported mainly to European countries, such as Poland (5455 tonnes), Denmark (5403 tonnes), the Netherlands (4248 tonnes), France (1997 tonnes), United Kingdom (1905 tonnes), and others (FAO Fisheries Division, Statistics and Information Branch, 2020). Future projections with business-as-usual scenarios expect the annual production of Icelandic land-based aquaculture to be tripled by 2032 (Government of Iceland 2023). Nevertheless, the integration of new technologies, increased number of fjords for ocean farming, and issuance of licenses permitting higher maximum allowed biomass (MAB), are projected to potentially elevate the country's aquaculture production to nine times its current level by 2032 (Government of Iceland 2023).

With the Earth warming at unprecedented speed due to anthropogenic emissions, changes to global food production, including aquaculture, are urgently needed (Zurek et al., 2022). Due to its geographical location, Iceland relies heavily on the importation of plant-based aquafeed ingredients, while fish-based ingredients are to a wide extent produced domestically (Sturludóttir et al., 2021). The production of these plant-based aquafeed ingredients for salmon farming in Iceland adds to the pressure on freshwater resources in the producing nations, and the water used to cultivate the crop becomes "embedded" in the aquafeed. This imported water is known as "exogenous water", as it is not native to the water resources of Iceland (or its "indigenous water") (Hoekstra et al., 2009). Similarly, carbon (and other greenhouse gases (GHG)) emissions associated with the production of the aquafeed ingredients used in salmon farming in Iceland thus include "embedded carbon" or "virtual carbon" from abroad, as the aquafeed is part of the fish farms production network (Peters, 2010).

The potential environmental impacts of the aquafeed production, including the quantity of water used, water deprivation potential to humans or ecosystems, and the greenhouse gas (GHG) emissions (also known as carbon footprint), can be assessed through Life Cycle Assessment (LCA) (ISO 2006a). Previous LCA studies have suggested that the primary contributors to water use in aquaculture are fish farming (i.e., the water required to cultivate the fish), and aquafeed production (i.e., the water needed to grow crops used in fish feed). Additionally, the aquafeed production is identified as the main contributor to the global warming potential (GWP) within the salmon farming life cycle (Vasquez-Mejia et al., 2023). Environmental impacts, including GWP of aquaculture with a focus on aquafeed, have been previously assessed (Maiolo et al., 2020; Tran et al., 2021; Wan et al., 2019; Ziegler et al., 2013), but with a limited focus on the water use of the aquafeed production.

There are currently two well-established methodologies that aim at understanding the freshwater use resources: the Water Footprint Assessment (WFA) developed by the Water Footprint Network (WFN), and the LCA-based approach. WFA allows for the quantification of direct and indirect water use needed for a product's production and is built with a supply chain thinking useful for water resource management (Hoekstra et al., 2009). The LCA-based water use assessment methods quantify the potential impacts of depriving human users and ecosystems of water resources (Kounina et al., 2013), which can be conducted with a Water Scarcity Footprint (WSF) assessment (ISO, 2014). *This LCA study aimed at quantifying the WSF, and the carbon footprint of producing all the aquafeed needed to farm salmon in Iceland, in both land-based and ocean-based settings in the year 2021.* Considering that the aquaculture sector in Iceland relies on the production of aquafeed ingredients from abroad, *the accounting phase of the WFA methodology was also included* to quantify the embedded water of the salmon feed from a supply chain perspective. Furthermore, the following research questions were addressed:

1) Are there any differences in the assessed environmental impacts associated with aquafeed used for the land-based or ocean-based salmon farming in Iceland, respectively?

2) What aquafeed ingredients are environmental hotspots, and why?

3) How does the country of origin of certain aquafeed ingredients affect their contribution to the carbon footprint, WSF, and water footprint accounting (WFA)?

4) Are there any environmental trade-offs between the WSF and the carbon footprint?

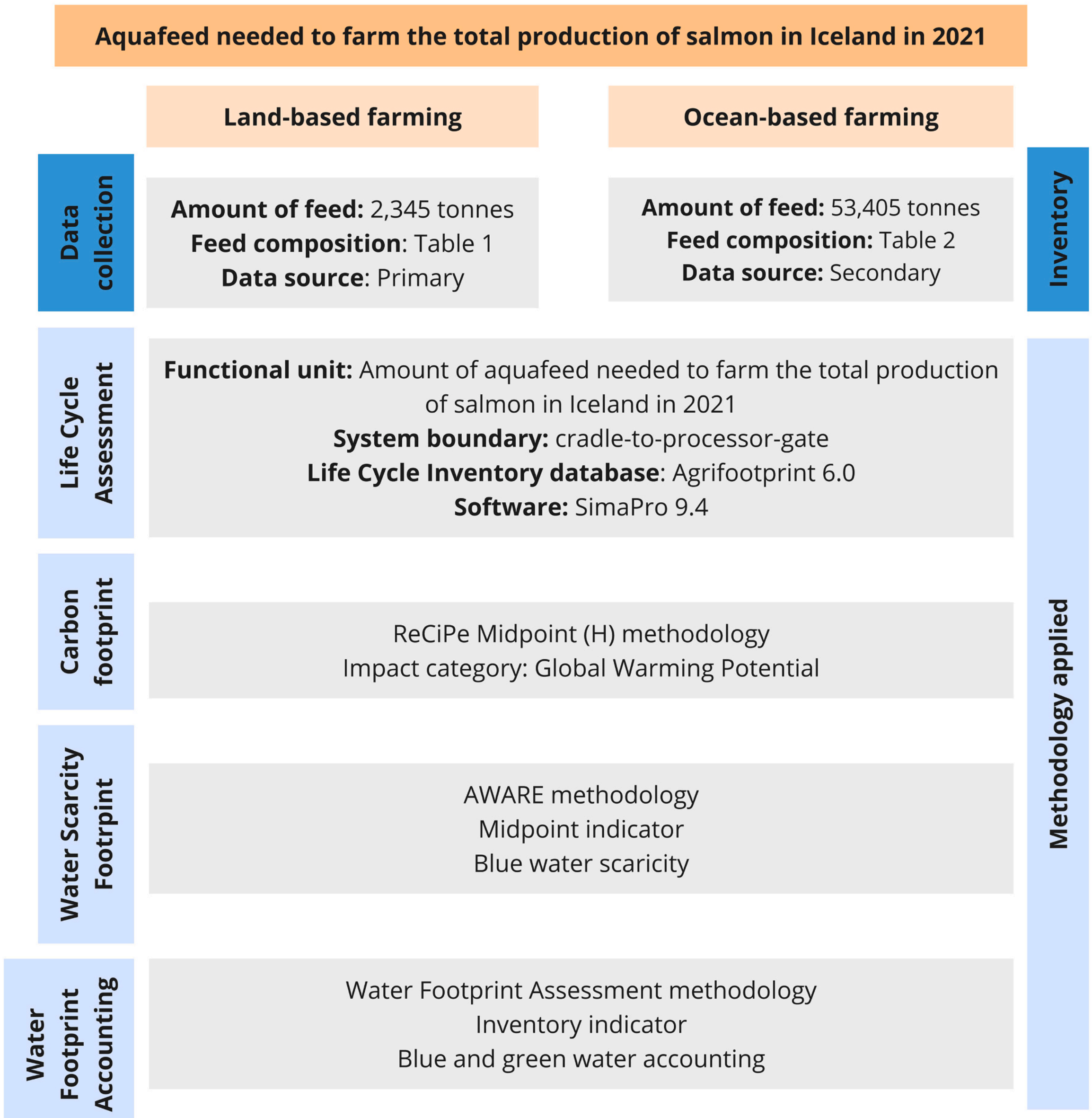

Fig. 1. Overview of data collection and methodology applied for carbon footprint, water scarcity footprint, and water footprint assessment.

The novelty of this study relies on being the first national-scale environmental assessment in Iceland to focus on the WSF and the carbon footprint of salmon aquafeed considering the most probable countries of origin of the ingredients used.

Table 1
Quantities and origin of feed ingredients used for salmon land-based aquaculture in Iceland in 2021. Feed composition values are based on wet weight.

Ingredient	Feed composition (%)	Quantity (tonnes)	Country of Origin
Fishmeal from by-catch	16	383	Iceland
Fishmeal from by-products	16	364	Iceland
Fish oil from by-catch	14	336	Iceland
Fish oil from by-products	10	224	Iceland
Soybean meal	16	374	Brazil
Wheat	12	280	Denmark
Maize gluten meal	16	374	China

2. Methods

Fig. 1 summarizes data gathering about the feed used in land-based and ocean-based salmon farming in Iceland and the methods applied in this study.

2.1. Life cycle assessment

2.1.1. Goal and scope

The goal of this study was to assess the WSF and carbon footprint associated with the aquafeed required to cultivate land-based and ocean-based salmon in Iceland using an *attributional LCA*. This study was defined and conducted following the ISO 14046:2006 and 14040:2008 guidelines for LCA, and the ISO 14044:2014 for the Water Footprint assessment (ISO 2006a, b, 2014). The functional unit (FU) of this study was defined as *the amount of aquafeed needed to farm the total production of salmon in Iceland in 2021 (1954 tonnes land-based, and 44,504 tonnes ocean-based)*. The system boundary was defined as cradle-to-processor-gate, which included the following activities: farming of plant ingredients, fishing for fish ingredients, transportation

Table 2
Country of origin and trade percentage contribution of aquafeed ingredients to the ocean-based Atlantic salmon farming in Iceland. Feed composition values are based on wet weight.

Ingredient	Country of origin	Trade contribution by ingredient (%)[a]	Quantity for Icelandic aquafeed (tonnes)[b]	Aquafeed composition (%)[c]
Soybean meal	Brazil	46 %	5146	21
	India	26 %	2893	
	China, mainland	14 %	1556	
	Netherlands	8 %	857	
	Denmark	3 %	292	
	Belgium	3 %	280	
	Germany	1 %	138	
Rapeseed or canola oil, crude	Russian Federation	38 %	3647	18
	Belarus	21 %	2056	
	Germany	13 %	1246	
	United Kingdom	7 %	698	
	Germany	6 %	542	
	Lithuania	5 %	451	
	Belgium	5 %	442	
Wheat gluten meal	China, mainland	73 %	3833	10
	Netherlands	6 %	310	
	Denmark	5 %	283	
	Ukraine	5 %	259	
	Hungary	4 %	229	
	Bulgaria	2 %	100	
	Turkey	2 %	92	
Fishmeal by-catch[d]	Iceland (FAO 27)	100 %	4700	9
Fish oil by-catch[d]	Iceland (FAO 27)	100 %	4433	8
Wheat	Germany	22 %	763	7
	Sweden	21 %	736	
	Poland	18 %	632	
	Russian Federation	10 %	344	
	Denmark	6 %	202	
	Lithuania	5 %	176	
	Estonia	4 %	139	
	Latvia	4 %	135	
	Belarus	4 %	133	
	Finland	3 %	102	
	Kazakhstan	2 %	74	
Guar protein	Not available	Not available	2296	4
Insect meal, single cell protein, others.	Not available	Not available	2190	4
Broad beans and horse beans, dry	United Kingdom	28 %	544	4
	Denmark	24 %	452	
	France	21 %	407	
	Poland	9 %	177	
	Estonia	6 %	114	
	Netherlands	6 %	108	
	Lithuania	4 %	75	
	Latvia	2 %	36	
Sunflower seed meal	Hungary	56 %	1025	3
	Russian Federation	39 %	703	
	Latvia	3 %	60	
	Lithuania	1 %	19	
	Bulgaria	0 %	5	
	Ukraine	0 %	2	
	Netherlands	0 %	1	
Fishmeal from cutoffs[d]	Iceland (FAO 27)	100 %	1762	3
Pea flour	Not available	Not available	1335	1
Fish oil from cutoffs[d]	Iceland (FAO 27)	100 %	1068	2
Pea protein	Not available	Not available	748	1

(*continued on next page*)

Table 2 (*continued*)

Ingredient	Country of origin	Trade contribution by ingredient (%)[a]	Quantity for Icelandic aquafeed (tonnes)[b]	Aquafeed composition (%)[c]
Oil of linseed	Russian Federation	82 %	571	1
	Belgium	17 %	120	
Corn gluten	Not available	Not available	374	< 1
Soybean oil	Russian Federation	29 %	62	< 1
	Netherlands	28 %	60	
	Denmark	21 %	45	
	Sweden	8 %	16	
	Germany	6 %	12	
	Belgium	4 %	9	
	Italy	3 %	5	
Camelina oil	Not available	Not available	214	< 1
Vitamins, minerals, amino acids, astaxanthin	Not available	Not available	214	< 1
Coconut oil	Not available	Not available	53	< 1

[a] Based on FAOSTAT trade database. Not available: not found in the database
[b] Calculated based on the requirements of each ingredient to produce the total aquafeed for salmon farmed in the ocean in Iceland in the year 2021
[c] Based on Aas et al., (2022)
[d] Country of origin based on FAO Fishing Areas (https://fish-commercial-names.ec.europa.eu/fish-names/fishing-areas_en)

of ingredients, and processing of the aquafeed (plant ingredients, fishmeal, and fish oil). A Feed Conversion Ratio (FCR) of 1.2:1 was assumed during the evaluation (Aas et al., 2022; Sturludóttir et al., 2021). Two scenarios were assessed: 1) Atlantic salmon production in the *land-based* farms in 2021, which resulted in 1954 tonnes of full-grown salmon at the farm-gate and consequently use of 2345 tonnes of feed. 2) Atlantic salmon production in the *ocean-based* farms in 2021, resulting in 44,504 tonnes of full-grown salmon at the farm-gate, and consequently use of 53,405 tonnes of feed.

2.1.2. System description and inventory analysis

2.1.2.1. Aquafeed for land-based salmon farming. Iceland produced 1954 tonnes of Atlantic salmon in land-based farms in 2021, of which 86 % of the production came from the Silfurstjarnan farm located in the north of Iceland (66.2197° N, 16.4683° W). Given the company's substantial market share in the production, it was used as basis to estimate the aquafeed required for land-based aquaculture operations on a national scale. Information on aquafeed composition and country of origin was provided directly by the company through a set of questionnaires, sent via email in August 2022. The Atlantic salmon grown in land-based farms were fed with locally processed 9 mm feed pellets with a low-fat content (24 %) coming exclusively from fish oil, in addition to three plant-based ingredients (soybean meal, wheat, and maize gluten meal) (Table 1). The aquafeed was processed in Iceland by Laxá Fiskafóður. Plant ingredients needed for the aquafeed were all imported, while the fishmeal and fish oil (FMFO) were produced domestically. Table 1 describes the quantities and origin of aquafeed ingredients used to farm salmon on land, with a FCR of 1.2, as expressed by the Samherji Fiskeldi and the latest food security report of Iceland (Sturludóttir et al., 2021).

2.1.2.2. Aquafeed for ocean-based salmon farming. Iceland farmed 44,504 tonnes of salmon in ocean-based settings. Given that Norwegian shareholders own the majority of salmon ocean farms in Iceland, and by the lack of access to primary data, it was assumed that the aquafeed used in these settings was comparable to Norwegian practices. Thus, a published report on aquafeed utilization in Atlantic salmon production in Norway was used as a baseline (Aas et al., 2022), using an assumed FCR of 1.2 (Aas et al., 2022; Sturludóttir et al., 2021). The feed for the ocean-based salmon farming contained more plant-based ingredients and a higher fat content (up to 37 %, of which 10 % came from fish oil) compared to the aquafeed for the land-based salmon farming. The difference in the diets between the two farming settings is attributed mainly to the ocean-based salmon requiring higher values of oil to resist the colder temperatures and wind exposure (Naylor et al., 2000). The origin of ingredients was estimated using the FAOSTAT crop and livestock products trade database (FAOSTAT, 2024). This search strategy provided an estimate of the market mix of each aquafeed ingredient in Norway and Iceland. However, one limitation of this approach was that it provided a national-level trade perspective but did not provide detailed information on where the aquafeed-producing companies were sourcing their ingredients. The information retrieved in the FAOSTAT database search was sorted based on the import quantity of each aquafeed ingredient to Norway, which resulted in multiple countries of origin for each ingredient. The export percentage contribution from these countries was considered in the rest of the analyses of this study. Aquafeed used for the ocean-based salmon aquaculture contained soybean meal (20 %), rapeseed oil (18 %), wheat gluten (9.8 %), fishmeal (8.8 %), fish oil (8.3 %), and other ingredients (Table 2). The FMFO origin was assumed to be sourced from FAO fishing area number 27, which includes Iceland (Aas et al., 2022; European Commission, 2024). Hence, it was assumed that the FMFO (both from cut-offs and by-catch) were processed in Iceland, and previous results by Hilmarsdóttir et al. (2022) on the environmental impacts of fishmeal and fish oil production in Iceland were used as the basis for calculation. The FMFO from targeted fish species was assumed to be from capelin, and FMFO produced from by-products was assumed to be from an Atlantic mackerel-herring Blend (MHB) (Hilmarsdóttir et al., 2022). Environmental impacts were allocated to fish oil or fishmeal (based on the production of one tonne of FMFO), as explained by Fréon et al. (2017). Table 2 summarizes the aquafeed composition for ocean-based salmon farming in Iceland and the estimated countries of origin for each ingredient.

2.1.2.3. LCI secondary datasets. Plant aquafeed ingredients processes used in the land-based and ocean-based salmon farming were selected from the Agri-footprint 6.0 mass-allocation database (developed by Mérieux NutriSciences and Blonk), and the electricity processes were selected from the Ecoinvent 3.8 database. If no Agri-footprint processes were available for the specific place of origin of the plant ingredients, the processes were modified to meet the conditions of the most probable place of sourcing (e.g., electricity origin mix, water use, land occupation and transformation, and emissions, such as ammonia, nitrogen monoxide, nitrate, and phosphorus). Broad beans from Denmark, which represent 24 % of the total amount of this ingredient needed for the Atlantic salmon ocean-farming in Iceland, can for example not be found in the Agri-footprint database. Thus, the broad bean production process from Germany was duplicated, and the geography of the electricity mix, elementary flows, and emissions were modified from Germany to Denmark. A complete list of the modified Life Cycle Inventory processes can be found in Online Resource 1. The agri-footprint 6.0 database considers the effect of peat emissions from drained soils on crop cultivation which was not available in earlier versions (Tyszler et al., 2023). Moreover, selected Agri-footprint processes contained values on water use for crop farming, processing, and background processes. Irrigation water and rainwater available in the preset processes of Agri-footprint 6.0 were based on values from Mekonnen and Hoekstra (2011).

2.1.3. Impact Assessment

LCA analyses were conducted in SimaPro 9.4. Mass allocation was used to handle multifunctional processes within the analysis.

2.1.3.1. Carbon footprint. Carbon footprint in LCA is a quantitative expression of total direct and indirect greenhouse gas (GHG) emissions associated with all activities throughout a product life cycle (Life Cycle Initiative, 2013). The Global Warming Potential (GWP) is an LCA midpoint impact category that allows a comparison of the global warming impacts of different GHGs over 100 years of lifespan and is often used to assess the carbon footprint of products (US EPA, 2016). GWP is measured as CO_2 equivalents (CO_2-eq), where one unit of CO_2 equals 1 unit of CO_2-eq, 1 unit of methane (CH_4) equals 27–30 units of CO_2-eq, and one unit of nitrous oxide (N_2O) equals 273 units of CO_2-eq (US EPA, 2016). The ReCiPe 2016 Midpoint (H) methodology was applied to assess the Global Warming Potential (GWP) of the aquafeed production for salmon farming in Iceland in both the land-based and ocean-based operations.

2.1.3.2. Water scarcity footprint (WSF). The AWARE method was used to assess the WSF. This is a mid-point indicator that considers the available blue water remaining after the aquatic ecosystemic and human needs have been met, and that is relative to the worlds̓ blue water availability minus the demand (AMD) result (AMD world=0.0136 m^3 m^{-2} $month^{-1}$) (Boulay et al., 2018). Therefore, the AWARE characterization factors (CF) are spatial-temporal specific, as the pressure on water resources changes among geographic locations and seasons (Boulay et al., 2018). The units used in WSF with the AWARE methodology are m^3 world-eq. and represent a cubic meter of consumed water on average in the world (Boulay et al., 2018). While this study aimed to assess the national-level impacts of aquafeed needed for salmon aquaculture production in Iceland, each aquafeed ingredient represents less than 5 % of its production capacity in the country of origin (e.g., 5147 tonnes of soybean meal from Brazil were required to produce the aquafeed for the ocean-based salmon farming in Iceland, which corresponds to 0.004 % of Brazil̓s total soybean production in 2021). Thus, based on the recommendations of the AWARE method developers (Boulay et al., 2020), marginal characterization factors (CF) were used. Moreover, the average of the AWARE CFs for the different water usage types (agricultural and non-agricultural), and for water use across all

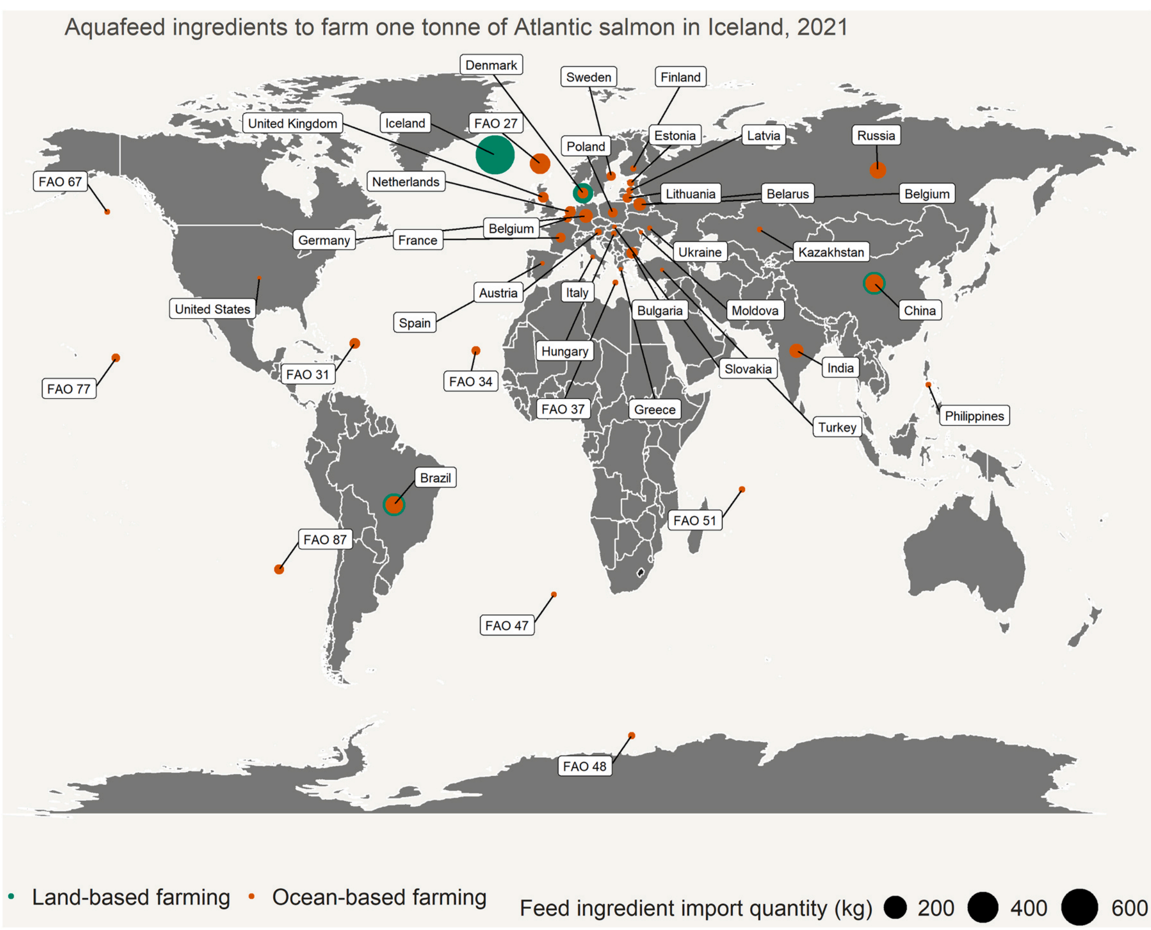

Fig. 2. *Amount of aquafeed ingredients sourced from around the world to produce one tonne of Atlantic salmon in Iceland in land-based (green data points) and ocean-based (orange data points) farms in 2021*. Each data point in the map represents the sum of ingredients sourced from a specific country to be used as feed for either land-based or ocean-based salmon farming. The size of each point on the map reflects the import quantity of each feed ingredient, as described in the figure legend. More details about which aquafeed ingredients and their quantities were sourced from specific countries can be found in Table 1 (for the land-based salmon farms) and Table 2 (for the ocean-based salmon farms).

months of the year, were used due to their availability on the SimaPro desktop software, and because the FU of this study was based on an annual production basis.

2.2. Water footprint accounting as described by WFA method

The Water Footprint Assessment (WFA) manual developed by the Water Footprint Network-WFN defines the water footprint of a product as the total direct and indirect freshwater appropriation to produce the product of interest (Hoekstra et al., 2009). It considers blue, green, and gray water footprints (WF), which are defined as follows: a) *blue water footprint* as an indicator of the consumptive use of fresh surface water or groundwater; b) *green water footprint* as the volume of rainwater consumed during a production process, which is especially relevant in agricultural processes due to the rainwater evapotranspiration from crops and soil, and the water uptake by the harvested crop (Hoekstra et al., 2009), and c*) grey water footprint* which refers to pollution (a measure of water degradation or quality), and is defined as the volume of freshwater required to assimilate a load of pollutants based on water quality standards (Hoekstra et al., 2009). The water footprint methodology as described by the WFA manual includes four stages: a) *setting goals and scope of analysis* by defining the purpose of the study and processes to include, b) *water footprint accounting* in which blue, green and grey water footprints are accounted for; c) *water footprint sustainability assessment*, in which environmental, social, and economic dimensions are considered at different geographical scales (local, river basin or global scales), and d) *water footprint response formulation* in which strategies to reduce the water footprint are defined, based on the hotspot evaluation obtained in the third step of the analysis. The *goal* of this study was to account the *blue and green water footprints* of the plant based aquafeed ingredients required to feed Atlantic salmon grown in land-based and ocean-based operations in Iceland in 2021. The *grey water footprint* was not included, as the water quality was beyond the scope of this study. Moreover, the water footprint sustainability assessment was excluded due to the complexity of the analyzed system and the included multiple feed ingredients sourced from various countries of origin.

Blue and green water footprint accounting values of producing one tonne of the ingredients of interest in different parts of the globe were taken from Mekonnen and Hoekstra (2011), and upscaled to the quantities required to meet the Icelandic salmon aquaculture demand. (Mekonnen and Hoekstra, 2011) considered a grid resolution level of 5 by 5 arc minutes (around 10 km by 10 km), incorporating factors such as local precipitation, crop water requirements, crop evapotranspiration, crop growing dates, and crop cultivation sites. The country-aggregated blue and green WF values of different agricultural crops reported by Mekonnen and Hoekstra (2011) were used in this study. Further details about this method can be found in their studies (Mekonnen and Hoekstra, 2011, 2010). FMFO was excluded from this analysis because its production does not require rainwater.

2.2.1. Data handling

Agricultural trade reports from the FAOSTAT database were consolidated in Microsoft Excel (Microsoft Office 365, 2016). The LCA analysis was conducted in SimaPro 9.4. (PRé Sustainability, Amersfoort, the Netherlands). Data sorting, visualization of life cycle impact assessment (LCIA) results, and maps were constructed in RStudio 2024.04 (Posit Software, Boston MA, U.S.A.).

3. Results and discussion

3.1. Supply chain of aquafeed ingredients for the Icelandic aquaculture sector

In 2021, aquafeed ingredients needed for land-based salmon farming in Iceland were sourced solely from four countries (Iceland, China, Brazil and Denmark, Table 1). Hence, the water footprint (both with AWARE and WFA), and the carbon footprint of producing each ingredient were linked to their unique country of origin. In contrast, aquafeed for ocean-based salmon farming required a more complex sourcing structure: 1.20 tonnes of aquafeed ingredients from over 41 places around the world are required per tonne of ocean-based salmon farmed in Iceland (Sturludóttir et al., 2021)(Table 2). FMFO was largely sourced (67 %) from fishing zone FAO27, which includes Icelandic waters, while plant-based ingredients were primarily processed in Norway, using raw material from China (0.10 tonnes of wheat gluten, soybean meal, and sunflower seed per tonne of ocean-farmed salmon), Brazil (0.10 tonnes of soybean meal per tonne of ocean-farmed salmon), Russia (0.08 tonnes of rapeseed oil, linseed oil, wheat, soybean oil, and sunflower seed per tonne of ocean-farmed salmon). The rest of the ingredients were provided from different countries in lower proportions (Fig. 2). The water stress of Iceland in 2021 was 0.39 %, which is quite low as opposed to major producing countries of the plant-based aquafeed ingredients which had larger water stress values. These included water stress values for i.e., China: 41.52 %, Brazil: 1.48 %, and Russia 4.12 % (AQUASTAT, 2021). This water stress indicator estimates the countrýs pressure on freshwater resources by main sectors (FAO, 2018). This means that Iceland's aquaculture sector relies on, and contributes to the pressure of, water-stressed countries to produce the aquafeed ingredients needed for both land-based and ocean-based salmon farms.

3.2. Carbon footprint of salmon aquafeed

Aquafeed needed for *land-based salmon farming* in Iceland in the year

Land-based salmon diet			Ocean-based salmon diet		
Ingredients	Aquafeed composition (%)	GWP (t CO_2-eq)	Ingredients	Aquafeed composition (%)	GWP (t CO_2-eq)
FMFO	56	610	FMFO	22	5.539
Maize meal	16	367	Soybean meal	21	36.312
Soybean meal	16	1.527	Rapeseed oil	18	10.596
Wheat	12	108	Wheat gluten	10	5.822
Electricity	NA	0	Wheat	7	1.571
			Broad beans	4	1.170
			Sunflower seed meal	3	1.453
			Linseed oil	1	1.245
			Soybean oil	<1	513
			Coconut oil	<1	123
			Electricity	NA	93
Total		**2.612**	**Total**		**63.709**

Fig. 3. *Carbon footprint measured as global warming potential (GWP) in tonnes of CO_2-eq of aquafeed required for the land-based and ocean-based farming of Atlantic salmon in Iceland in the year 2021*. The red columns represent the proportional contribution (%) of each ingredient to the total water GWP.

Land-based salmon diet			Ocean-based salmon diet		
Ingredients	Aquafeed composition (%)	AWARE (m^3-world eq)	Ingredients	Aquafeed composition (%)	AWARE (m^3-world eq)
FMFO	56	151,598	FMFO	22	1,363,878
Maize meal	16	417,936	Soybean meal	21	3,724,118
Soybean meal	16	19,026	Rapeseed oil	18	620,323
Wheat	12	4,057	Wheat gluten	10	20,645,176
Electricity	NA	256	Wheat	7	145,413
			Broad beans	4	93,200
			Sunflower seed meal	3	142,978
			Linseed oil	1	512,802
			Soybean oil	<1	226,076
			Coconut oil	<1	3,915
			Electricity	NA	124,429
Total		592,618	Total		27,247,888

Fig. 4. *Water scarcity footprint (m^3- world equivalent water use) as obtained with the AWARE methodology of the aquafeed required for land-based and ocean-based farming of Atlantic salmon in Iceland in the year 2021, respectively*. The blue columns represent the proportional contribution (%) of each ingredient to the total water scarcity footprint score.

2021 was responsible for 2612 tonnes of CO_2-eq (or 1.3 tonnes CO_2-eq per tonne of salmon at farm-gate) emissions. Although soybean meal comprised only 16 % of the feed, it was responsible for 58 % of the total GHG emissions (Fig. 3), primarily due to land use change, diesel use in farming, fertilizer application, and concrete use in infrastructure. FMFO, the main ingredient in the land-based salmon aquafeed, contributed 23 % of the total GHG emissions, mainly from the diesel burned in the fishing vessels (Fig. 3). Maize meal and wheat contributed 14 % and 4 % respectively, with emissions largely from fertilizer use and diesel for agricultural machinery. Electricity used in aquafeed production added another 406 kg CO_2-eq.

Feed used in *ocean-based salmon farming* in Iceland in the year 2021 was responsible for 64,437 tonnes of CO_2-eq (or 1.5 tonnes CO_2-eq per tonne of salmon at farm-gate) (Fig. 3). The main ingredients contributing to the carbon footprint were soybean meal (55 %), rapeseed oil (16 %), wheat gluten (9 %), and FMFO (8 %), with remaining ingredients contributing less than 2 % each. Soybean meal, which was 21 % of the aquafeed formulation and largely sourced from Brazil (Fig. 3/Table 2), contributed to the carbon footprint mainly by CO_2 emitted by land transformation, diesel burned in agricultural production, and fertilizer use. These results were obtained from the contribution tree in SimaPro for the corresponding Agri-footprint process (Soybean meal (solvent), market mix, at regional storage {BR} Mass, U). Rapeseed oil was the second largest carbon footprint contributor due to dinitrogen monoxide emissions from fertilizer use, carbon dioxide emissions from machinery use, and land transformation. The wheat gluten (10 % of the aquafeed composition) impact was mainly attributable to diesel and fertilizer use in the farming stage (43 %). Nevertheless, electricity and heat used at the wheat gluten processing stage contributed to 31 % and 26 % of carbon footprint, respectively.

The carbon footprint of producing aquafeed for one tonne of full-grown salmon at farm-gate in the land-based farms was 1.3 tonnes CO_2-eq, and 1.5 tonnes CO_2-eq in the ocean-based farms (Fig. 3). The difference between the systems is relatively low and can be attributed to the higher use of soybean meal in the ocean-based settings (21 % compared to 16 % in land-based salmon farms). These results are comparable to an LCA study on salmon farming in Scotland, where 2.0 tonnes CO_2-eq were emitted for every tonne of head-on-gutted (HOG) salmon at the processor gate, and the main contributor towards GWP were vegetable proteins, such as soybean meal (Newton and Little, 2018).

Land-based salmon farming					
Ingredient	Aquafeed composition (%)	Blue WF (m^3)	Green WF (m^3)	Total (m^3)	Blue-Green contribution
Soybean meal	16	374	959,684	960,058	
Maize meal	16	24,310	261,426	285,736	
Wheat	12	1,680	148,400	150,080	
Total		26,364	1,369,510	1,395,874	
Ocean-based salmon farming					
Ingredient	Aquafeed composition (%)	Blue WF (m^3)	Green WF (m^3)	Total (m^3)	Blue-Green contribution
Soybean meal	21	536,228	32,627,025	33,163,253	
Rapeseed oil	18	-	37,645,825	37,645,825	
Wheat gluten	10	4,109,406	10,202,383	14,311,788	
Wheat	7	13,319	3,536,712	3,550,031	
Broad beans	4	11,406	572,646	584,052	
Sunflower seed meal	3	3,170	1,774,413	1,777,583	
Linseed oil	1	120,421	6,727,448	6,847,869	
Soybean oil	<1	589	228,719	229,308	
Total		4,794,538	93,315,170	98,109,709	

Fig. 5. *Blue and green water footprint accounting of aquafeed destined for land-based and ocean-based farming of Atlantic salmon in Iceland in the year 2021 as obtained with the WFA methodology*. Blue and green columns represent the proportional contribution (%) of each ingredient to the total blue and green water requirements, respectively. The last column represents the proportional blue/green water contribution of each ingredient.

As a carnivorous species, Atlantic salmon relies on fish-based ingredients like FMFO (Bendiksen et al., 2003). Reducing FMFO use is as a strategy to lower dependency on wild aquatic ecosystems and the net primary production use (NPPU), which are biotic resources no longer available for other systems (Boissy et al., 2011; Maiolo et al., 2020; Papatryphon et al., 2004). However, limits to substitution with plant ingredients are set by fish health, growth, and nutritional requirements (Oliva-Teles, 2012). In this study, the land-based salmon farming had 56 % FMFO in their diet composition, compared to 22 % in the ocean-based farmed salmon. The traceability of FMFO is challenging as it is often sold as a blend of various species, as a mechanism to ensure consistency in quality and availability of a product that is extremely variable depending on species and seasonality, and is highly perishable (Tacon, 2005). Thus, it can be difficult to pinpoint the exact location of the FMFO source and account for it in LCAs. The current study assumed that this ingredient was fully sourced from Iceland, and that the processing facilities were fueled by hydropower, which is the optimal conditions available in Iceland (Hilmarsdóttir et al., 2022). While these assumptions are plausible to operating conditions in FMFO processing facilities in Iceland, GHGs emissions from FMFO production plants in other parts of the world are most likely higher, as they often operate on heavy fuel oil (Hilmarsdóttir et al., 2022). Future studies on the environmental impacts of aquafeed could focus on providing better strategies to backtrace the origin of the fish for FMFO and their fishing practices, perhaps by setting up effective communication routes with processing facilities. Also, detailed information on processing factors, such as the energy source and cooking temperature for the FMFO manufacturing is recommended for more detailed assessments (Hilmarsdóttir et al., 2022).

3.3. Water scarcity footprint of aquafeed

Aquafeed needed to farm salmon in the *land-based* facilities in Iceland in the year 2021 was responsible for 592,874 m^3 world-eq. of freshwater used (or 304 m^3 world-eq. per tonne of aquafeed) (Fig. 4). Although maize gluten comprised only 16 % of the feed composition, the maize gluten meal was responsible for 71 % of the total WSF of the land-based salmon farming (Fig. 4). The contribution network of the selected maize gluten meal process in SimaPro (Maize gluten meal dried, at processing {CN} Mass, U), indicated that cultivation of the grain carried 82 % of the water use impact, and the remaining 18 % occurred during the processing stages. Within the cultivation stage, water use needed to grow the crop was the largest contributor (96 %), and electricity use was the main contributor within the processing stages. Soybean meal sourced from Brazil contributed 3 % to the total WSF of the land-based salmon in 2021 (Fig. 4). Similar to the maize gluten meal, 86 % of the water use for the soybean meal occurred within the cultivation stages. However, the production of sulfuric acid for fertilizers (global market processes) and concrete (global market process) needed for infrastructure were the largest contributors to the WSF of the soybean cultivation in Brazil (the unique country of origin of soybean meal used in aquafeed for land-based salmon farming in Iceland; Table 2), and not the actual water required to farm it, which was 0.44 m^3 world-eq. FMFO had the largest share in the aquafeed composition (56 %), and its WSF was 26 % (151,598 m^3 world-eq. per land-based salmon farmed in the year 2021 in Iceland) of the total WFS of the feed for the salmon farmed in the land-based settings (Fig. 4). Based on a previous LCA study of FMFO production in Iceland, it was assumed that this ingredient was processed locally in a factory run mainly on hydropower (Hilmarsdóttir et al., 2022), as stated earlier. Thus, its contribution to the total WSF of the land-based aquafeed was assessed to largely originate from high-voltage electricity use.

In 2021, the WSF of the aquafeed used for *ocean-based* salmon farming in Iceland totaled 27.6 million m^3 world-eq (or 620 m^3 world-eq. per tonne of aquafeed) (Fig. 4). Wheat gluten, although comprising only 10 % of the feed, was the major contributor, responsible for 75 % (20.6 million m^3 world-eq.) of the total WSF. This ingredient was largely sourced from China, and 96 % of its water use occurred during wheat cultivation, as indicated in the contribution network for the wheat gluten process in SimaPro. Soybean meal, the most abundant ingredient in the feed (21 %), contributed to 13 % (3.7 million m^3 world-eq.) to the WSF (Fig. 4). While mainly sourced from Brazil (46 %), much of the soybean meal water impact was linked to soybean irrigation in the U.S., due to the global nature of the market mix reaching regional storage in China, Germany, and the Netherlands. FMFO, comprising 22 % of the feed, accounted for 5 % of the WSF. Rapeseed oil, with 18 % of the feed formulation, contributed less than 2 %, with most water use resulting from fertilizer application during cultivation. Other ingredients (e.g., broad beans, sunflower seed meal, coconut oil, linseed oil, soybean oil, and wheat) also had minimal impact on the overall (Fig. 4).

3.4. Water footprint accounting as described by WFA method

The accounted blue and green water footprints (WF) of the plant ingredients needed to farm Atlantic salmon in the *land-based* operations in Iceland in the year 2021 were 26,364 m^3 and 1369,510 m^3, respectively (1.4 million m^3 of freshwater in total; Fig. 5). In other words, 2 % of the total WF of the aquafeed ingredients originated from *blue water*, and 98 % from *green water*. Each tonne of plant aquafeed used to farm salmon in the land-based operations consumed 26 m^3 and 1332 m^3 of freshwater in the form of *blue and green water*, respectively. Among the *blue WF* of the aquafeed needed to farm salmon in the land-based operations in Iceland, the maize meal, wheat, and soybean meal contributed to 24,310 m^3, 1680 m^3, and 374 m^3 of used freshwater, respectively. *Green water* (or rainwater) was mostly required by the soybean meal (959,684 m^3), maize gluten meal (261,426 m^3), and wheat (148,400 m^3) productions (Fig. 5).

The combined *blue and green WF* of the aquafeed crops used in 2021 in Iceland to farm Atlantic salmon in *ocean-based* settings was 98,109,709 m^3 of freshwater, of which 95 % was *green water*, and 5 % was *blue water* (Fig. 5). Each tonne of the evaluated aquafeed ingredients for the ocean-based aquaculture required 144 m^3 of *blue water* and 2793 m^3 of *green water*. Within the analyzed aquafeed ingredients, wheat gluten contributed 86 % of the *blue WF* (or 4.1 million m^3 of freshwater) of the aquafeed used in the ocean-based salmon farming in Iceland. *Green WF* of aquafeed used in the ocean-based salmon farming was largely caused by the rapeseed oil production (37.6 million m^3 of freshwater, or 40 % of the total green WF contribution), and soybean meal (32.6 million m^3, or 35 % of the total green WF contribution) (Fig. 5). Maize meal and wheat gluten ingredients for the land-based and ocean-based salmon farming, respectively, had the largest share contribution of *blue water* to the *blue/green water footprint accounting* (Fig. 5). Mekonnen and Hoekstra (2011) explained that higher fractions of accounted blue water footprint are expected in arid or semi-arid regions where water scarcity is higher, such as China, where maize meal and wheat gluten are mainly sourced from.

A previous global WFA study estimated 1912 m^3 of freshwater were needed per tonne of aquafeed for Atlantic salmon, composed of 79 % green, 9 % blue, and 12 % grey water (Pahlow et al., 2015). These results are comparable to our findings where combined *green and blue water footprints* per tonne of aquafeed were 595 m^3 and 1837 m^3 for the land-based and ocean-based salmon farming, respectively, with a higher contribution from *green water* (98 % and 95 % for the land-based and ocean-based aquafeed, respectively). Although both studies shared similar feed compositions, differences emerged in ingredient-specific footprints. For instance, Pahlow et al. reported that corn gluten meal required 9712 m^3 green and 833 m^3 blue water per tonne, whereas this study, using China-specific data (Mekonnen and Hoekstra, 2011), reported much lower values: 699 m^3 green and 65 m^3 blue water. These discrepancies likely stem from Pahlow's use of global averages and non-specific sourcing, in contrast to this study's spatially explicit

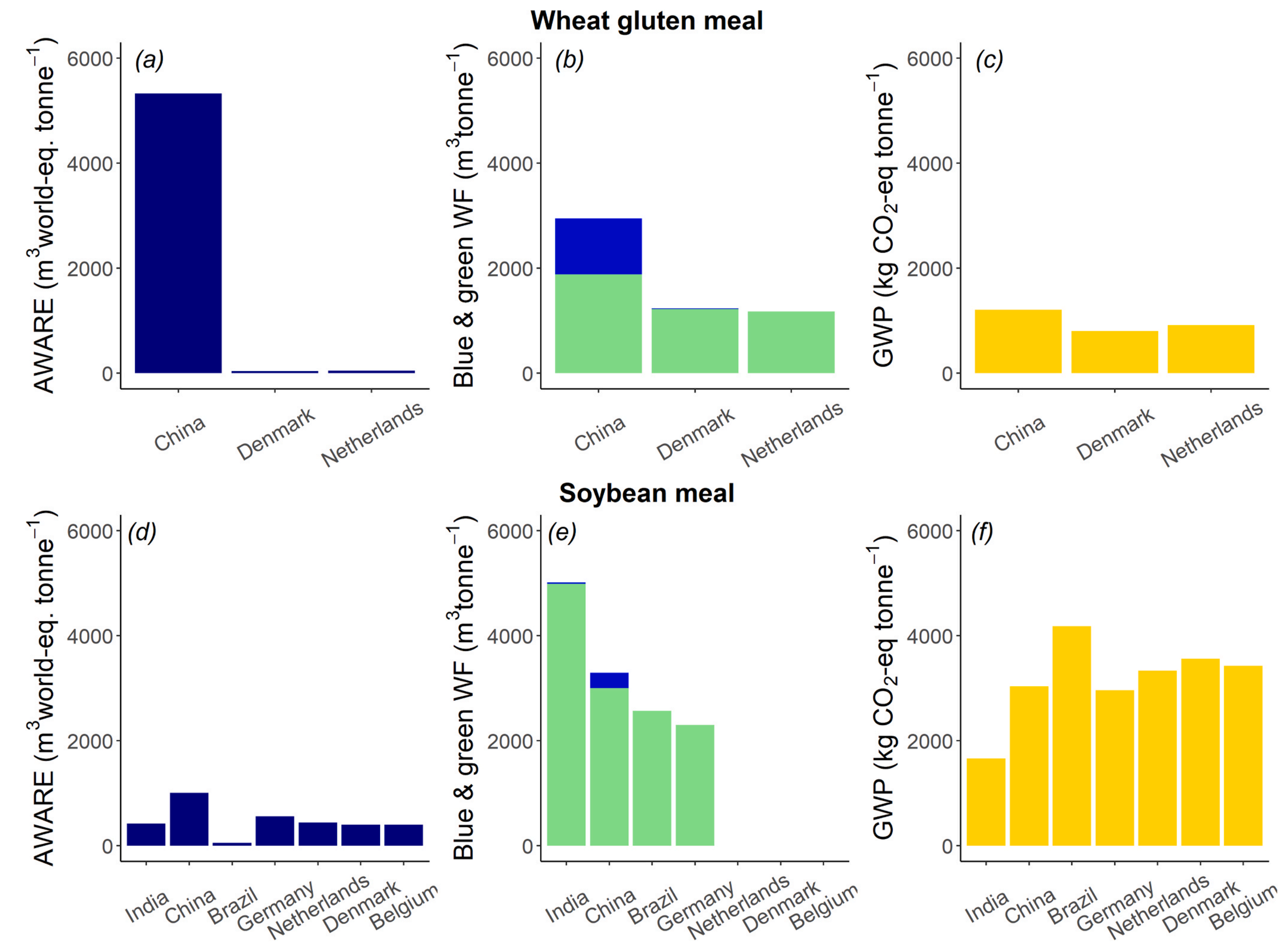

Fig. 6. *AWARE, blue and green WF, and GWP of selected aquafeed ingredients sourced from different countries of origin.* a) *AWARE* results of producing one tonne of *wheat gluten meal* in different countries. b) Blue and green water footprints (WFA) of producing one tonne of *wheat gluten meal* in different countries. c) *carbon footprint* of producing one tonne of *wheat gluten meal* in different countries. d) *AWARE* results of producing one tonne of *soybean meal* in different countries. e) Blue and green water footprints (WFA) of producing one tonne of *soybean meal* in different countries. f) *carbon footprint* of producing one tonne of *soybean meal* in different countries.

approach. Moreover, Pahlow et al. (2015) assumed that the WF (blue, green, and grey) of FMFO was negligible because it was sourced from the ocean. However, this overlooks indirect freshwater use in FMFO processing, particularly for hydropower and cleaning—highlighted in recent literature (Hilmarsdóttir et al., 2022).

Water consumed in rain-fed agriculture is only *green water*, while irrigated agriculture includes both *green water* (rainfall) and *blue water* (irrigation) (Hoekstra, 2003). On average, the reported yields of irrigated crops are higher than in rain-fed crops, because the latter depends entirely on rainfall stored in the soil profile (Hoekstra, 2003; Mekonnen and Hoekstra, 2011). This means that one tonne of irrigated crops has a lower consumptive (blue and green) water footprint than one tonne of rain-fed crops (Mekonnen and Hoekstra, 2011). The environmental impacts of rainwater appropriation for agricultural purposes are linked to past land-use decisions (e.g., transformation of natural vegetation to agricultural land), and thus the reallocation of green water flows (Schyns et al., 2019). However, water footprint accounting, as conducted in this study, does not measure the effects on biodiversity and ecosystems of using green water for aquafeed production.

3.5. *Assessed environmental impacts of selected aquafeed ingredients based on their country of origin*

3.5.1. *Wheat gluten*

Wheat gluten used in Icelandic salmon aquafeed in 2021 was primarily imported from China (73 %), with smaller shares from the Netherlands (6 %), Denmark (5 %), and Ukraine (5 %) (Table 2). The wheat gluten contribution to the 2021 global production market (769 Mt) of the abovementioned countries was 18 %, < 1 %, 1 %, and 4 %, respectively (FAOSTAT, 2024). These sourcing patterns reflect varying environmental impacts due to country-specific production practices and water scarcity contexts.

3.5.1.1. Water Scarcity Footprint. The WSF of wheat gluten production varied by country of origin, largely due to differences in regional water scarcity and irrigation practices. China exhibited the highest WSF at 5330 m^3 world-eq. per tonne of wheat gluten, compared to lower values for the Netherlands (46 m^3), Denmark (36 m^3), and broader Europe (239 m^3) (Fig. 6a).The reasoning behind this assessment is that the potential of water deprivation to other users or ecosystems is greater if there is less water remaining per area (Boulay et al., 2018). Therefore, the potential impacts of water deprivation by using 1 m^3 of fresh blue water in regions with different water scarcity indexes should not be considered equally (Boulay et al., 2018). Recent AWARE developments include the calculation of specific AWARE CF of crops when produced in different countries by linking the irrigation specificities of each crop to the related cultivated areas, and the water basins from which blue water is sourced at the sub-national level (Boulay et al., 2019). This would result in wheat farmed in China having a CF of 66.8, instead of 42.3 as the aggregated AWARE CF applied in this study, and thus also have an even higher blue water scarcity footprint (31,114 m^3 world-eq. tonne of wheat at the farm gate) (Boulay et al., 2019), instead of 5330 m^3 world-eq. (Fig. 6a), which could be interpreted as potential higher risks of water scarcity-related issues with wheat farming in China (Boulay et al., 2019).

3.5.1.2. Water Footprint Accounting. Disaggregated green and blue water use further revealed geographic differences. Wheat gluten from China required 1881 m^3 of green water and 1068 m^3 of blue water per tonne, indicating considerable irrigation demand. In contrast, wheat gluten from the Netherlands and Denmark was primarily rainfed, with green water footprints of 1171 m^3 and 1216 m^3 , and minimal blue water use (0 m^3 and 15 m^3, respectively)(Fig. 6b). These results represent country-aggregated values, but sub-national variation in water use patterns also affect WFA outcomes. For example, in southern China's Anhui province, wheat gluten production is predominantly rainfed, with 91 % of the water footprint attributed to green water and only 9 % to blue water—comparable to water use patterns in Denmark and the Netherlands, where blue water use is minimal. In contrast, wheat farming in northern China, such as in the Shandong province, shows a markedly different profile, with 54 % green water and a considerably higher 45 % blue water contribution (Mekonnen and Hoekstra, 2011). This elevated reliance on irrigation in Shandong reflects broader agronomic challenges, as wheat cultivation in northern China often does not align with the seasonal rainfall, resulting in significant irrigation demand (Kang et al., 2017). Consequently, this region faces heightened water scarcity pressures, despite being a major wheat-producing area. In response, agronomic research has focused on improving crop water productivity through the development of drought-resistant wheat varieties and advancements in irrigation efficiency. However, recent assessments have called into question the long-term viability of wheat farming in such water-stressed regions, highlighting the unsustainable strain it places on local freshwater resources (Huang et al., 2019).

3.5.1.3. Carbon footprint. Contrary to WSF, the carbon footprint of the wheat gluten production was not majorly explained by the farming stage, and the processing stage also emitted GHG by its associated electricity and heat (natural gas) use. One tonne of wheat gluten produced in China resulted in 1205 kg CO_2-eq (Fig. 6c) of which 41 % was from the farming stage, 32 % from electricity use, and 24 % from heat (natural gas) used in furnaces. Among the farming stage, emissions were predominantly explained by fertilizers emissions, diesel burned in machinery, and peat oxidation, which are carbon emissions linked to drained peat soil for agriculture (Tyszler et al., 2023). The Netherlands emitted 911 kg CO_2-eq per tonne of wheat gluten produced (Fig. 6c), of which 44 % came from farming in different parts of Europe, 23 % from electricity used during processing, and 33 % from heat used during processing. Lastly, Denmark produced 796 kg CO_2-eq per tonne of wheat gluten processed (Fig. 6c), of which 50 % came from farming (fertilizer use, peat oxidation, and machinery use), 37 % from heat use during processing, and 13 % from electricity use. No land transformation was associated with the farming of wheat in the described locations, only land occupation. Peatlands, naturally occurring wet environments, are estimated to store twice as much carbon in their soil as the global forest biomass, despite covering only 3 % of the world's land area (Humpenöder et al., 2020). Anthropogenic interventions in peatlands, such as their drainage to use the land for agricultural purposes such as wheat farming, result in peat oxidation and the release of stored carbon in the form of CO_2 (Worrall et al., 2010). Results from this study show that peat oxidation from wheat cultivation in China and the Netherlands contributed to GWP with 0.8 kg CO_2 eq and 117.2 kg CO_2 eq per tonne of ingredient farmed, respectively.

3.5.2. Soybean meal

Soybean meal was largely sourced from Brazil (46 %), India (26 %), and China (14 %) (Table 2). These countries contributed to the 2021 global production market of soybean meal (372 Mt) by 36 %, 3 %, and 4 %, respectively (FAOSTAT, 2024).

3.5.2.1. Water scarcity footprint. The WSF (AWARE) of producing one tonne of soybean meal differed between Brazil, India, and China, with reported values of 53 m^3 world-eq., 419 m^3 world-eq., and 1002 m^3 world-eq., respectively (Fig. 6d). The main contributors to the WSF of Brazilian soybean meal production were the market for sulfuric acid for fertilizers (46 %), and the market for concrete slab (20 %). Soybean meal produced in China contains a market mix of dried soybeans farmed in different parts of the globe (48 % from Brazil, 30 % from the United States, 14 % from China, and 6 % from Argentina). Yet almost half (49 %) of the WSF of this soybean mix came from the United States, and the other half (48 %) from China. Soybeans sourced from Brazil that were processed into soybean meal in China carried 2 % of the total WSF (AWARE).

3.5.2.2. Water footprint accounting. Green water was the dominant source across all countries (Fig. 6e). India had the highest green water consumption, with 4991 m^3 $tonne^{-1}$ of soybean meal, and only 26 m^3 of blue water. Chinese production involved 2999 m^3 of green water and 293 m^3 of blue water per tonne. In Germany, 2296 m^3 of green water were reported, with no blue water footprint. Brazil showed relatively low blue water use (1 m^3 $tonne^{-1}$), and a green water footprint of 2566 m^3 $tonne^{-1}$.(Mekonnen and Hoekstra, 2011) (Fig. 6e). However, sustainability concerns extend beyond water use. Ayala et al. (2016) projected that soybean farming in the Amazon, although within green water sustainability limits in 2010, could surpass sustainable thresholds by 2050 under current land use and management practices, potentially compromising regional vegetation water needs.

3.5.2.3. Carbon footprint. Carbon footprint assessment of soybean meal ranged from 1661 to 4182 kg CO_2-eq per tonne of feed ingredient, depending on its producing country (Fig. 6f). The largest contribution of the Brazilian soybean meal production to the carbon footprint was CO_2 emissions from land transformation (85 %) to farm the crops, followed by emissions from machinery use (3 %), and natural gas heating for processing (3 %). It has been estimated that Brazil transformed 1.4 Mha $year^{-1}$ of Amazon rainforest and Cerrado savannah to produce 36 % of the global soybean production in 2021 (165 Mt) (Marin et al., 2022). This land transformation practice leads to the uplift of warmer and drier air and a blockage of downwind moisture transport from the ocean and ultimately changes in the water budget (Xu et al., 2022). In other words, land use change can be a major contributor to the carbon footprint, while simultaneously altering a region's water availability (Xu et al., 2022). This underscores a key limitation in both AWARE and WFA methodologies: while they quantify direct water use, they do not account for the indirect effects of land transformation on water availability. Consequently, sourcing decisions based solely on lower WSF or blue/green WF values could overlook critical environmental trade-offs. For example, Brazil appears favorable in terms of WSF and water footprint (Fig. 6d–e), yet carries a disproportionately high global warming potential (GWP) due to land conversion impacts.

In contrast, soybean meal sourced from India had the lowest carbon footprint (1661 kg CO_2 eq $tonne^{-1}$), with 33 % attributed to land transformation, 28 % to fossil fuel use in farming, 15 % to N_2O emissions from fertilizers, and 10 % to processing energy.

3.6. Blue water scarcity footprints (AWARE) vs. green/blue water footprint accounting (WFA manual)

This study employed both the AWARE method and the Water Footprint Accounting (WFA) approach to assess water use in aquafeed production. While AWARE is an LCA-compliant indicator that evaluates the potential environmental impacts of blue water use through water scarcity weighting (Boulay et al., 2018), the WFA method provides a volumetric inventory of both green and blue water consumption (Hoekstra et al., 2009). These two approaches are not directly comparable due to their different purposes—impact assessment (AWARE) vs. inventory analysis (WFA)—yet they are complementary and can be used together to inform water sustainability strategies, as emphasized in the published opinion letters and discussions on this topic (Boulay et al., 2013; Hoekstra, 2016; Pfister et al., 2017).When analyzing water scarcity footprint results from this study from an LCA perspective, it becomes evident that efforts to reduce these impacts should be placed on sourcing aquafeed ingredients from less water-scarce countries (e.g., obtaining wheat gluten meal from other countries than China, maize meal from China, and soybean meal from India and China, Fig. 4 and Fig. 6). Therefore, AWARE results (LCA-based) from this study provided a detailed local perspective to the impacts related to water use for aquafeed produced at the multiple places of origin of each plant-based ingredient. One limitation of this study is the exclusion of existing LCIA methods to assess potential impacts on terrestrial green water flows and reductions in surface blue water production caused by land-use production systems, or land-occupation (and thus appropriation of soil moisture that is no longer available for the natural ecosystem) (Pfister et al., 2017; Quinteiro et al., 2015).

Blue and green WF accounting of producing plant-based aquafeed for salmon farming in Iceland proved to be useful in understanding the amount (in terms of volumetric values) of water that is required to produce all the plant aquafeed ingredients to feed salmon farmed in both land-based and ocean-based salmon farms in Iceland. Moreover, it allowed differentiation between green and blue water flows, which are useful when looking at the water system at a global scale in terms of virtual water trade, such as in this study that encompassed a supply chain perspective.

4. Conclusions

The carbon footprint and water scarcity footprint were calculated for aquafeed used in the land-based and ocean-based salmon farming in Iceland in 2021. Results from this study suggest that the aquafeed needed per tonne of ocean-based salmon farmed had a higher water scarcity footprint and blue/green water accounting footprints (WFA) compared to the aquafeed needed per one tonne of land-based farmed salmon. The hotspot analysis by ingredients showed that maize meal and wheat gluten, both sourced from China, were the major contributors to the WSF (AWARE) in land-based and ocean-based salmon aquaculture, respectively. In other words, ingredients sourced from China contributed to a higher water deprivation potential to humans and ecosystems, compared to sourcing from other less-water-scarce countries The WFA results suggest that the embedded water of imported aquafeed for land-based and ocean-based salmon farming in Iceland is largely rainwater (green water), and the largest contributors to the green water accounting footprint in land-based and ocean-based salmon farming were soybean meal and rapeseed oil, respectively.

The carbon footprint of the aquafeed needed for one tonne of the land-based or ocean-based salmon farmed was similar. Soybean meal sourced from Brazil was the major contributor to the carbon footprint of aquafeed used in land-based and ocean-based salmon farming, which was largely explained by land-use change in the Amazon rainforest. Results from this study also showed that soybean meal was a major contributor to the carbon footprint but not to the blue water scarcity footprint, and wheat gluten showed the opposite results, suggesting environmental trade-offs between carbon and water scarcity footprint for the abovementioned ingredients.

This study is novel as it is the first national-scale assessment in Iceland to focus on the carbon footprint and water use of salmon aquafeed production, considering the most probable countries of origin of the ingredients used and their water stress index. Moreover, understanding how different feed ingredients contribute to selected environmental impact categories can support the aquaculture sector in the reformulation of feed to reduce the environmental footprint. While this study focused on Icelandic aquaculture, the results can be transferable to other countries that source their ingredients from the same locations. Moreover, the present study provided a new optic to the believed self-reliance of farmed fish production in Iceland, as it exposes the aquaculture industry's dependency on feed ingredients sourced from other countries, and the hidden water and carbon footprints that these ingredients carry. Hence, efforts to reduce water use and carbon emissions in the aquaculture sector should be focused on the hidden water and carbon footprints associated with the feed. Future research on this topic should include LCA assessments, including AWARE, of potential environmental benefits and trade-offs of new feed ingredients, such as insect meal, micro- and macroalgae, and/or single-cell proteins. In addition, future research should explore further water quality in feed production and other aspects of sustainability, such as the social and economic dimensions.

CRediT authorship contribution statement

Sveinsdóttir Hildur Inga: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Smáradóttir Heiðdís:** Writing – review & editing, Validation, Resources. **Hilmarsdóttir Guðrún S.:** Writing – review & editing, Validation, Software, Resources, Methodology. **Manzardo Alessandro:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Vasquez-Mejia Clara Maria:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gudjónsdóttir María:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Ögmundarson Ólafur:** Writing – review & editing, Validation, Supervision, Software, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Hildur Inga Sveinsdottir, Maria Gudjonsdottir, Olafur Ogmundarson reports financial support was provided by Horizon Europe. Maria Gudjonsdottir, Olafur Ogmundarson reports financial support was provided by ERA-Net Cofund scheme. Maria Gudjonsdottir, Olafur Ogmundarson reports financial support was provided by The Icelandic Centre for Research. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109528.

Data Availability

Data will be made available on request.

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