STAKEHOLDER PERCEPTIONS AND SUSTAINABLE INTENSIFICATION STRATEGIES FOR EUROPEAN AQUACULTURE

by

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Abstract

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Global trade is central in supplying the growing demand for seafood in Europe, leading to a dependency on finite capture fisheries and aquaculture imports. Urbanisation and rising global income levels drive demand for high-value carnivorous species already farmed in Europe, indicating growth opportunities. However, European aquaculture lacks scale, and growth capacity is undermined by cheaper alternatives. Additionally, European aquaculture is dependent on imported feed ingredients, responsible for most of the costs and environmental impact. Therefore, the aim is to explore two promising sustainable intensification strategies using a stakeholder perceptions survey, nutritional and volume analysis of processing by-products, and a LCA of (novel) feed ingredients. Firstly, strategic processing and utilisation of by-products into food, feed and industrial applications could increase the (economic) output, without the need for additional resources. We find that substantially higher total flesh yield can be achieved if fully processed, compared to fillet only. While large volumes of nutritious Atlantic salmon by-products are utilised, there is potential to increase volumes and value. Available by-product volumes from European seabass, gilthead seabream, common carp, and turbot with interesting nutritional characterisation (e.g., protein, lipids and/or EPA+DHA content) could be increased if more strategically processed. By-products which are unattractive for food applications, with low ash content, could improve the sustainability of animal feed provisioning in Europe as well. Secondly, ingredients that are produced in (semi-)arid areas in Europe, therefore not competing for agriculture resources, while minimizing environmental impact, should be favoured, such as guar and microalgae meal. In theory, these strategies combined show potential to increase the resource efficiency, economic performance, competitiveness, resilience, and environmental sustainability. However, in practice, potential varies between aquaculture species and geographical location, mostly affected by infrastructure barriers and consumer preferences. The importance of knowledge and technology transfer between species and production systems, to overcome these barriers, is emphasised.

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I dedicate this work to my daughter, partner, parents, sister, grandparents, and friends. I am grateful for all the support.

DECLARATION

The work described in this thesis was undertaken by the candidate and embodies the results of his own research. Where appropriate, the nature and work carried out by others has been fully acknowledged.

Wesley Malcorps

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

ABBREVIATIONS/ ACRONYMS	**DEFINITION**
ANFs	Anti-Nutritional Factors
AP	Acidification Potential
Approx.	Approximately
B2B	Business-To-Business
BAU	Business As Usual
BP	By-products
BWU	Blue Water Use
Cat.	Category
CEU	Cumulative Energy Use (renewable or non-renewable)
CF	Conversion Factor
CFCs	Chlorofluorocarbons
CH	Chapter(s)
DM	Dry Matter/Dry Meal
EEA	European Economic Area (EEA), includes the European Union (EU) member states, Iceland, Liechtenstein, and Norway
eFIFO	economic Fish In: Fish Out ratio
EISI	Eco-intensification Sustainability Index
EP	Eutrophication Potential
Eq	Equivalent
EU	European Union
EURASTiP	The European Asian aquaculture Technology and innovation Platform
FA	Fatty Acid
FAQ	Fair Average Quality
FCR	Feed Conversion Ratio
FIFO	Fish In: Fish Out
FM	Fishmeal
FO	Fish Oil
FP7	7th Framework Programme for Research
FPH	Fish Protein Hydrolysate
FTE	Full-Time Equivalent
FU	Functional Unit
(G)VC(A)	(Global) Value Chain (Analysis)
GAIN project	Green Aquaculture Intensification in Europe project
GHG	Greenhouse Gas
GMO	Genetic Modified Organism
GWP	Global Warming Potential
H2020	Horizon 2020 - Research and Innovation - European Union
Ha	Hectare
HFCs	Hydrofluorocarbons
HOG	Head-On-Gutted
IFFO	The Marine Ingredients Organisation
IIM-CSIC	Instituto de Investigaciones Marinas
Indust.	Industry
IoA	Institute of Aquaculture
KI	Key Informant
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LC-PUFA	Long-Chain Polyunsaturated Fatty Acids
LU	Land Use

LUC	Land Use Change
LW(E)	Live Weight (Equivalent)
m2a	Square Meter Per Annum
(M)MT	(Million) Metric Tonne
n.a.	not applicable
Nat. grid	National grid energy mix
NO	Norway/Norwegian
Non-r.	Non-renewable
OECD	The Organisation for Economic Co-operation and Development (38 member countries)
OLD	Ozone Layer Depletion
PCOPCO	Photochemical Oxidation
PEFCR	Product Environmental Footprint Category Rules
PLN	Polish złoty (zł)
PO	Poland/Polish
R.	Renewable
RAS	Recirculating Aquaculture System
S.	Scenario
SBM	Soybean Meal
SDG	Sustainable Development Goal
SEAT project	Sustaining Ethical Aquatic Trade project
SME	Small and Medium-Sized Enterprise
Sust.	Sustainable
tkm	Tonne per kilometer
UK	United Kingdom
UoS	University of Stirling
USD	US Dollar ($)
WW	Wet Weight
ZUT	West Pomeranian University of Technology (Zachodniopomorski Uniwersytet Technologiczny w Szczecinie)

SPECIES NAME AND DESCRIPTION

SPECIES	SCIENTIFIC NAME/DESCRIPTION
Alaska pollock	*Gadus chalcogrammus*
Arctic char	*Salvelinus alpinus*
Argentine red shrimp	*Pleoticus muelleri*
Atlantic salmon	*Salmo salar*
Bighead carp	*Hypophthalmichthys nobilis*
Blue mussel	*Mytilus edulis*
Bream	*Abramis brama*
Cod	*Gadus morhua*
Common carp	*Cyprinus carpio*
European catfish	*Silurus glanis*
European hake	*Merluccius merluccius*
European seabass	*Dicentrarchus labrax*
Gilthead seabream	*Sparus aurata*
Grass carp	*Ctenopharyngodon idella*
Guar or cluster bean	*Cyamopsis tetragonoloba* and varieties (*Pusa Naubahar* and *Pusa Sadabahar*)
Hake	*Merlucciidae* family
Japanese carpet shell/manila clam	*Ruditapes philippinarum*
Meagre	*Argyrosomus regius*
Mediterranean mussel	*Mytilus galloprovincialis*
Microalgae	*Tetraselmis suecica*
Microalgae	*Tisochrysis lutea*
Microalgae	*Nannochloropsis sp.*
Microalgae	*Isochrysis sp.*
Microalgae	*Schizochytrium sp.*
Mussel	*Mytilus spp.* + other mussels
Nile tilapia	*Oreochromis niloticus*
Pacific "cupped" oyster	*Crassostrea gigas / Magallana gigas*
Perch	*Perca fluviatilis*
Pike	*Esox Lucius*
Pikeperch	*Sander lucioperca*
Rainbow trout	*Oncorhynchus mykiss*
Roach	*Rutilus rutilus*
Saith	*Pollachius virens*
Senegalese sole	*Solea senegalensis*
Shrimp	Warmwater shrimps, cold water shrimps, deep-water rose shrimps, shrimp *Crangon spp.* and miscellaneous shrimps
Silver carp	*Hypophthalmichthys molitrix*
Tench	*Tinca tinca*
Tuna	Skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*), bluefin (*Thunnus thynnus*) and miscellaneous
Turbot	*Psetta maxima*
Warmwater shrimps	Mainly the giant tiger prawn (*Penaeus monodon*) and the white leg prawn (*Litopenaeus vannamei*)

CHAPTER 1: SUSTAINABLE INTENSIFICATION OF EUROPEAN AQUACULTURE TO ENHANCE THE RESILIENCE OF THE SEAFOOD MARKET

1.1 Problem statement

Domestic European Union (EU-28) seafood consumption increased by 25% from 2005 to 2017 to 24.4 kg capita^{-1} year^{-1} (EUMOFA, 2018a; EUMOFA, 2019a), while it slightly declined to 22.6 kg capita^{-1} year^{1} in 2021 as a result of market disruption caused by Brexit, the pandemic and fuel crisis (Turenhout *et al.*, 2022). Within Europe, seafood consumption quantities are highly variable, from 6.34 up to 57.19 kg capita^{-1} year^{-1} for Hungary and Portugal in 2019, respectively (FAOSTAT, 2023). Nevertheless, overall seafood consumption in the European (EU-27) diet is still relatively low, as it accounted for 11.5% of the g capita^{-1} day^{-1} animal protein intake, compared to 16.5% for the global diet (FAOSTAT, 2023). Europe's relatively low dietary seafood inclusion (FAOSTAT, 2023), in combination with a relatively high household income compared to other global regions (Hirvonen *et al.*, 2019), indicates potential for increased consumption. Additionally, seafood is a crucial source of omega-3 (n-3) long-chain polyunsaturated fatty acids (LC-PUFA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are important micronutrients for human and animal health (Tocher *et al.*, 2019; Hamilton *et al.*, 2020; Hirvonen *et al.*, 2019). It can also improve intake of other key micronutrients such as vitamin D and B12, iodine, selenium and other minerals (Aakre *et al.*, 2019), as well as being a good source of bioavailable protein. A moderate consumption of seafood in the Global North could lower the large footprint associated with ruminant meat consumption, while reducing risk of cardiovascular disease (Crona *et al.*, 2023). These benefits show great potential for stimulating increased consumption.

The EU Live Weight Equivalent (LWE) seafood supply of 12.89 million Metric Tonnes (MT) in 2020 originated from domestic capture fisheries (23%) and aquaculture production (9%) in 2020, with the rest of the balance supplied by imports from non-EU member states derived from capture fisheries (52%) and aquaculture (16%) (Figure 1.1). The dependency on global trade and finite capture fisheries for the supply of healthy and nutritious seafood into the EU is clear (Bostock *et al.*, 2016; STECF, 2023; EUMOFA, 2022). This is also reflected by the low self-sufficiency ratio of 42% (ten-year average), indicating the EU seafood production capacity to meet domestic demand. However, it declined significantly to 35% in 2021, because of reduced catches and the UK exiting the EU (Turenhout *et al.*, 2022). Regarding the latter, directly affecting the EU trade balance, as the UK (6%) is considered the third most important seafood trade partner after Norway (26%) and Morocco (6%) in terms of volume and value of fisheries and aquaculture products imported into the EU in 2021, respectively (EUMOFA, 2022). Salmonids (97% salmon (*Salmo salar*), 3% trout (*Oncorhynchus mykiss*) and others) are the main seafood species imported, mainly from Norway

(European Economic Area (EEA) member), and since 2021 also from the UK, supplying a total of 17% (volume) and 25% (value) of fisheries and aquaculture products in 2021. The second most imported species was cod (*Gadus morhua*), in which Norway also supplied the majority of the supply (EUMOFA, 2022).

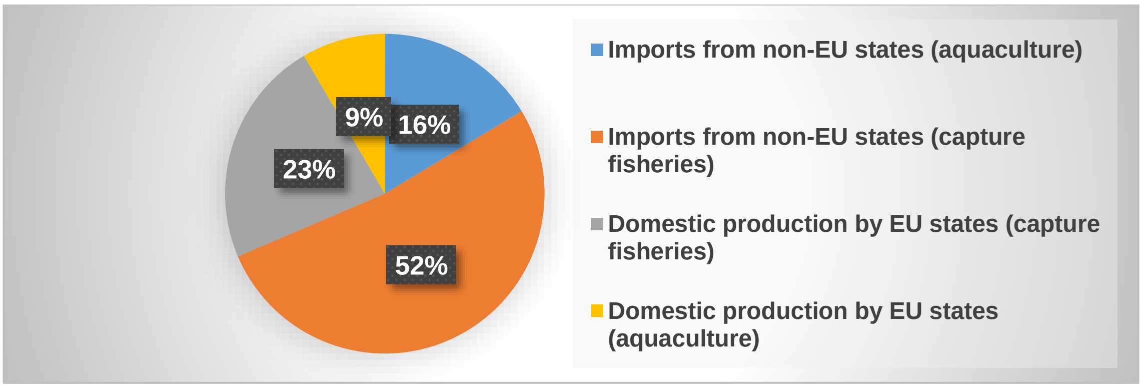


Figure 1.1: The EU LWE seafood supply balance of 12.89 million MT for fisheries and aquaculture products in 2020, according to EUMOFA (2020b), based on EUROSTAT and FAO data.

Bivalves (e.g., mussels, oysters and clams) represented more than half (Live Weight Equivalent (LWE), incl. shells) of the total EU aquaculture production (Ferreira and Bricker, 2015), from which mussel production makes up a third of the total EU aquaculture production (Avdelas *et al.*, 2020). However, considered on an EEA resolution, bivalves make up approx. 20% of the total aquaculture production (FAO, 2023b). The most important species covering most of the bivalve production are the blue (*Mytilus edulis*) and Mediterranean (*Mytilus galloprovincialis*) mussels, Pacific cupped oyster (*Crassostrea gigas*), and Japanese carpet shell/manila clam (*Ruditapes philippinarum)*. In addition to a nutritious supply of seafood, bivalve aquaculture also provides ecosystem services, such as carbon sequestration, nutrient removal, coastal protection and increased biodiversity (Olivier *et al.*, 2020). Therefore, bivalves show promising characteristics to support the sustainable growth of aquaculture, but it is challenged by multiple factors, such as food safety concerns, production inefficiencies, limited availability of convenience products and low consumer demand (Willer, Nicholls and Aldridge, 2021). Bivalve's contribution to global food supplies is also overestimated in direct comparison with finfish supply, as FAO statistics report wet weight equivalents (including inedible shell), while their edible meat yield averages 17%, compared to the edible yield of finfish average at 87% (Edwards *et al.*, 2019; Belton *et al.*, 2020). Additionally, in terms of mussels, while they are relatively affordable, demand is limited (Belton *et al.*, 2020), while the sector in the EU is also challenged by low profitability, lack of seed (spat) and disease (Avdelas *et al.*, 2020), and added competition from Chilean mussel imports lowering prices in the EU market (Salazar and Dresdner, 2022). In contrast to the increasing trend of global mussel production, EU production was declining over the past two decades (Avdelas *et al.*, 2020). However, an increase in the overall production of finfish species, such as Atlantic salmon, European seabass and gilthead seabream compensated this trend (Figure 1.2, (FAO, 2023b)), resulting in a stagnation of the overall EU aquaculture production

(Avdelas *et al.*, 2020). The sudden decline in 2020 was the result of the UK, and their associated Atlantic salmon, rainbow trout and bivalve production, leaving the EU (Figure 1.2).

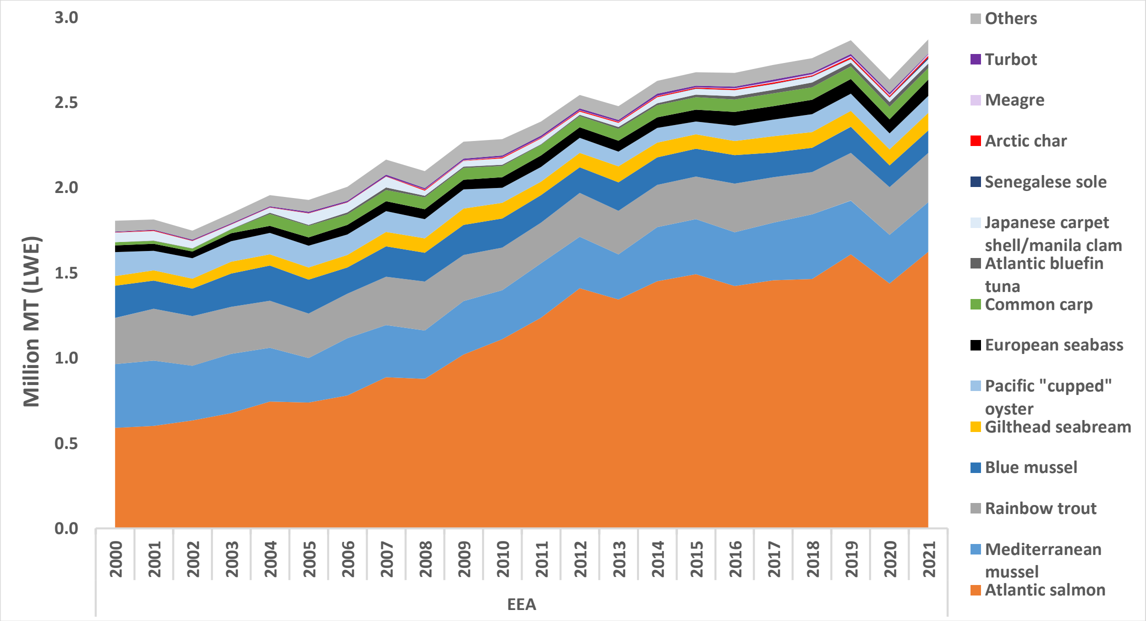


Figure 1.2: Most important EEA aquaculture species production from 2000-2021. Species included if production was >7,500 MT in 2021, except for turbot, which is included based on historic production volumes and market potential (FAO, 2023b).

The most important finfish species in terms of production volumes and market are Atlantic salmon (*Salmo salar*), rainbow trout (*Oncorhynchus mykiss*), European seabass (*Dicentrarchus labrax*), gilthead seabream (*Sparus aurata*), common carp (*Cyprinus carpio*) and turbot (*Psetta maxima*). Figure 1.2b excluded the Atlantic bluefin tuna (*Thunnus thynnus*) "fattening industry", as it is considered value-added fisheries by Benetti *et al.* (2016). Others, such as the Senegalese sole (*Solea senegalensis*), Arctic char (*Salvelinus alpinus*) and meagre (*Argyrosomus regius*) are upcoming aquaculture species (Figure 1.2b), but due to their historical low production volumes and limited market potential out of the scope of this thesis.

The preference for high-value species, such as Atlantic salmon, is expected to continue as a result of rising income levels and urbanisation (FAO, 2018). Nevertheless, while marine finfish aquaculture has grown rapidly, it is challenged by the high cost of production in terms of feed and energy inputs and technological requirements for offshore sites (Belton *et al.*, 2020; O'Shea *et al.*, 2019). Consequently, it retails for a relatively high price for consumers, making it inaccessible to low-income households (Belton *et al.*, 2020). Additionally, most of the environmental impacts of fed aquaculture (marine and freshwater) are related to feed production (Henriksson *et al.*, 2018; Marín *et al.*, 2019). Therefore, expansion of fed aquaculture, including offshore finfish production increases demand for land, freshwater and other (agricultural) resources (Henriksson *et al.*, 2018; Marín *et al.*, 2019). Generally speaking, fed mariculture and freshwater aquaculture show comparable environmental footprints in terms of different Life Cycle Analysis (LCA) impact categories, such as

Global Warming Potential (GWP), Land Use (LU), Eutrophication Potential (EP) and impacts on biodiversity (Gephart *et al.*, 2021; Cottrell *et al.*, 2018)), while fuel consumed by boats to offshore finfish farms contributes significantly to the GWP, CEU, OLD and AP (García García *et al.*, 2016; Belton *et al.*, 2020).

It is important to recognize the interlinkages between aquaculture, fisheries, and agriculture, which vary by location. Therefore, strategies in terms of (environmental) governance, conservation, trade, and food distribution could vary depending on the geographical challenges in this regard. It is considered important to further develop aquaculture with low environmental impacts (Blanchard *et al.*, 2017). While semi-intensively (low feed input) produced common carp shows potential in terms of nutrition, affordability and environmental sustainability, demand is low (Belton *et al.*, 2020; Raftowicz and Le Gallic, 2019). According to Belton *et al.* (2020), increasing affordable and sustainable aquatic food requires investment and policy development in freshwater aquaculture. More specifically, a focus on herbivorous and omnivorous freshwater fish, such as tilapia, carp and catfish that consume relatively cheaper terrestrial plant ingredients (Hua *et al.*, 2019) is highly desirable. These species fulfil and important role in global food security, as they are accessible and affordable for the low- and middleclass consumers mainly in low- and medium-income countries (Zhang *et al.*, 2022; Belton, Bush and Little, 2018). It is therefore important to prioritise the development of freshwater aquaculture in terms of investment, research, and policies, while also recognizing the role and co-development of mariculture (Zhang *et al.*, 2022). Freshwater aquaculture shows great potential to grow through horizontal expansion and intensification, while fed mariculture is more resource-constrained (Zhang *et al.*, 2022). This is challenging for European aquaculture, as fed mariculture, such as Atlantic salmon, dominates the aquaculture species portfolio (Figure 1.2).

1.2 Sustainable intensification strategies

Changes in consumer demand, development of complex food standards (safety and quality), technology advances and changes in industry structure have resulted in the downstream agri-food value chain being responsible for most of the final food price paid by consumers compared to the upstream value chain (Humphrey and Memedovic, 2006; Goldsmith *et al.*, 2002). In particular, small-scale fishers and fish farmers receive a small proportion of the total value for their products, compared to processors and retail markets due their stronger bargaining power (Bjørndal *et al.*, 2015). In broad terms, there would naturally be a tendency to accumulate more value towards the market-end of the chain, in particular for value chains where greatest value is placed on fresh products (personal communication, Prof. Jimmy Young (2023)). In general terms, there will tend to be some concentration of value along the seafood value chain for several reasons. Critical is that seafood processing is a weight-reducing activity due to the historical tendency to focus primarily upon those parts of the product most desired. Whilst technical innovation, new product development and changing market demands (more value-added products/ processes etc) will alter shares over time the broad tendency remains (personal communication, Prof. Jimmy Young (2023)).

It is crucial to develop the (European) aquaculture industry in a sustainable way by means of sustainable intensification (Little *et al.*, 2018), using land, water and nutrients efficiently, while minimizing the negative impact on ecosystems and biodiversity (FAO, 2011; Foley, 2011). A range of studies indicate that growth could take place beyond the production of fish (farm-gate), such as in processing, marketing and further down the value chain (Asche, Bjørndal and Young, 2001; Zidack, Kinnucan and Hatch, 1992). The use of the whole fish needs to be made a more explicit part of sustainability thinking and communicated to stakeholders, especially retailers and consumers. By-products make up a large proportion of the whole fish and therefore strategic utilisation in food, feed and industrial application could increase volume and value output significantly, as shown in the study of Stevens et al. (2018). It could potentially transmit more value across the value chain.

On the other hand, most of the aquaculture production costs and environmental impacts are associated with the upstream value chain related to feed input (Bohnes *et al.*, 2018; Rana, Siriwardena and Hasan, 2009). According to a study by Asche & Oglend (2016) there is a clear and increasing correlation between salmon price and feed input (e.g., fishmeal (FM), soybean meal and wheat), which is commonly observed for maturing commodity industries such as the Norwegian salmon industry where price trends will move from productivity driven to input-factor price driven. Dependency on (imported) terrestrial crops and wild fish for feed and associated price fluctuations and environmental impacts affects its resilience (Troell *et al.*, 2014), emphasizing an opportunity to explore the use of novel feed ingredients. Altogether, the use of certain novel feed ingredients (upstream) and the strategic utilisation of fish by-products (downstream) could increase the volume and value of the aquaculture industry without the need for additional resources, which is further explored in section 1.2.1, 1.2.2 and Figure 1.3.

1.2.1 Upstream

Feed provisioning is a crucial component in the sustainable intensification process (Little *et al.*, 2018). European aquaculture is highly dependent on imported marine and terrestrial ingredients, such as FM, fish oil (FO) and soy (Newton and Little, 2018), making the industry vulnerable to external (economic) shocks and therefore less resilient (Troell *et al.*, 2014). Additionally, feed application covers most of the cost and environmental impact of fed aquaculture production (Bohnes *et al.*, 2018; Rana, Siriwardena and Hasan, 2009). While there are environmental concerns regarding the use of FM/FO, this is also the case for their substitutes, such as plant derived meals and concentrates (Newton and Little, 2018; Blanchard *et al.*, 2017; Malcorps *et al.*, 2019a). It is therefore crucial to reduce aquafeed’s reliance on (imported) FM/FO produced from forage fish (Froehlich *et al.*, 2018), and plant ingredients originating from productive agricultural land, which is already under pressure to meet demand for human food, terrestrial livestock feed, biofuels and biobased materials (Spiertz and Ewert, 2009; Godfray *et al.*, 2010). While some novel feed ingredients, such as insects and microalgae show promising characteristics, they do not always deliver on their promises to improve environmental sustainability (Maiolo *et al.*, 2020b). Additionally, (constant) nutritional quality, availability, and price of novel feed ingredients remains a challenge (Pelletier *et al.*, 2018; Hua *et al.*, 2019). In this regard, the second sustainable intensification strategy is to explore affordable and available feed ingredients with nutritional potential, while having a minimal impact on the marine and terrestrial ecosystem. It is important that they do not compete significantly with other agricultural crop production and their respective resources, such as land, freshwater and fertilizer (Figure 1.3).

1.2.2 Downstream

Readily available resources in the form of fish by-products could be more efficiently processed and utilised for human consumption, animal feeds and industrial applications (Stevens *et al.*, 2018). This would increase the production in terms of volume and value output, without the need for additional resources (Stevens *et al.*, 2018), a perfect example of sustainable intensification (Figure 1.3). While this strategy benefits the sustainability of downstream processing, it could indirectly improve the sustainability of animal feed provisioning in Europe as well.

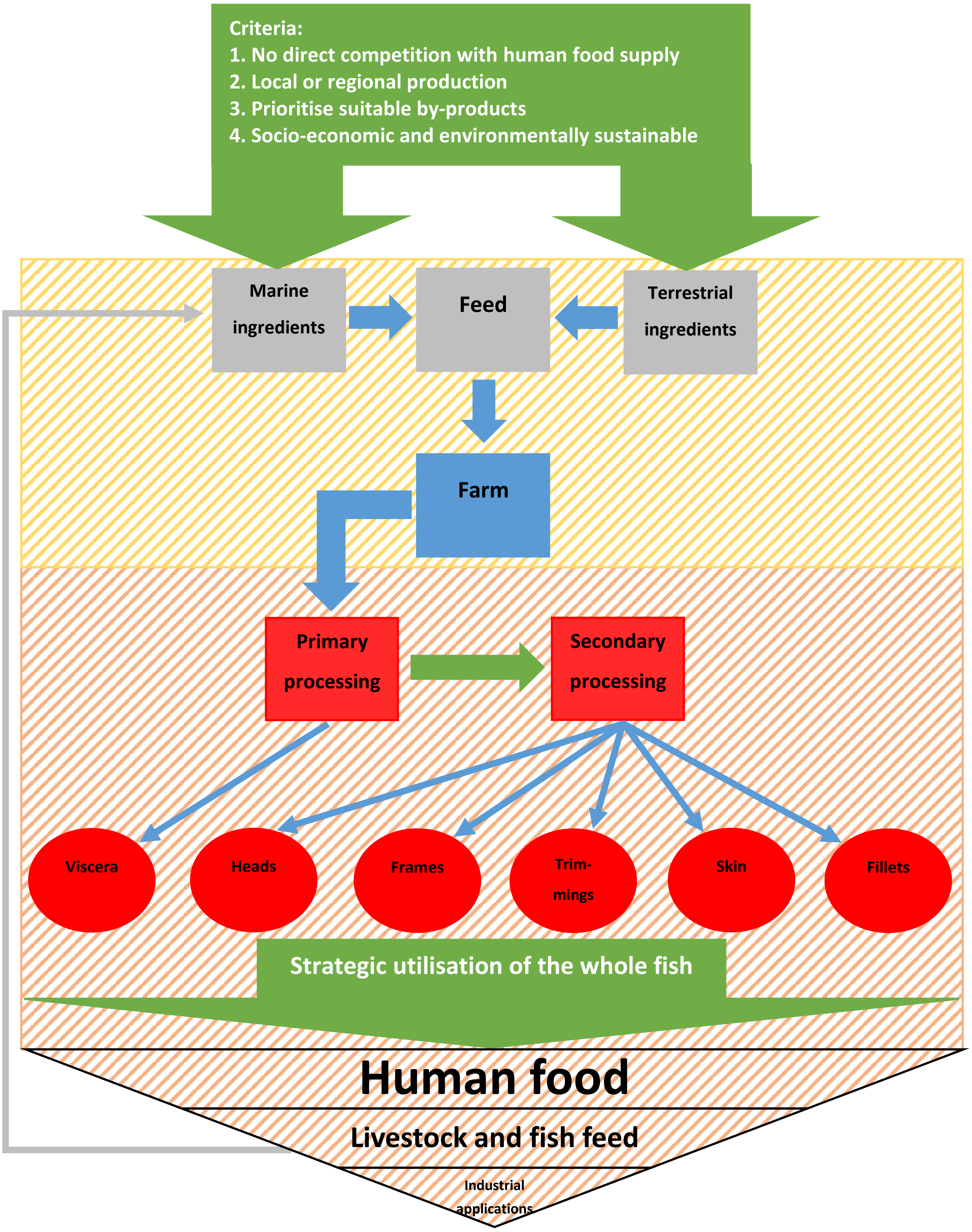


Figure 1.3: A simplified upstream (yellow pattern) and downstream (orange pattern) aquaculture value chain with opportunities for sustainable intensification (green). Material flow and main farm production in blue, processing, and by-products in red, such as heads, frames (the central skeleton of the fish including the tail), trimmings (fin offcuts), skin (incl. scales) and viscera (internal organs) suitable for food, feed, or industrial applications. Food recovery hierarchy is based on Stevens et al. (2018). Figure made by author.

1.3 Research questions and thesis roadmap

It is relatively unknown, which, and to what extent sustainable intensification strategies could support the growth (volume and value) of the European aquaculture industry. A better understanding of sustainable intensification strategies could reduce the reliance on seafood and aquafeed imports and increase the resilience of the European seafood market.

Formulation of the main research question and sub-questions:

1. **What are suitable sustainable intensification strategies for European aquaculture?**

1.1 What are the stakeholder perceptions towards sustainability and intensification strategies?

1.2 What is the underutilised aquaculture processing by-product potential (volume and nutritional characterisation)?

1.3 Which novel feed ingredients show potential to enhance sustainability and resilience (low environmental footprint, regionally produced, no competition with human food supply)?

1.4 What type of messaging strategies are applied to globally traded seafood products?

The roadmap for this study is visualised in Figure 1.4. A literature review forms the basis of this thesis and is focussing on the EU seafood market and the current state of EEA aquaculture. This includes production, processing, trade, and consumption, as well as discussing the sustainable intensification strategies for European aquaculture in more detail. This was achieved by developing an understanding of the development and sustainability of European aquaculture in the literature review (CH2), which also briefly explored the sector using the five value chain themes described in the study of Bush *et al.* (2019). This formed the basis of the stakeholder perception study (CH3), assessing the suitability and role of certain stakeholders and their perceptions on the industry, sustainability, and sustainable intensification strategies. Close attention needs to be paid to the different perceptions of stakeholders along the value chain to identify opportunities and challenges for sustainable intensification. This is important because (environmental) impacts are highly variable along the value chain depending on species and production system, especially in highly complex global supply chains (Poore and Nemecek, 2018; Waite *et al.*, 2014).

The lessons learned from the stakeholder perception study laid the foundation for more specific research into the strategic utilisation of fish by-products (CH4) and novel feed ingredients (CH5) to support the sustainable intensification of European aquaculture. Growth without using more resources is crucial to reduce the reliance of the European seafood market on global trade in terms of seafood and aquafeed ingredients. However, this requires a shift towards more regional production and trade, as well as associated messaging strategies to convey production processes and sustainability aspects between traders and the market.

CH6 explores messaging strategies used by business-to-business seafood traders who often function as a choice editor for final consumers. A better understanding of messaging strategies, culture and interpretation can improve communication of production characteristics, and in turn improve the sustainability of products, better meeting the expectations of the final consumers.

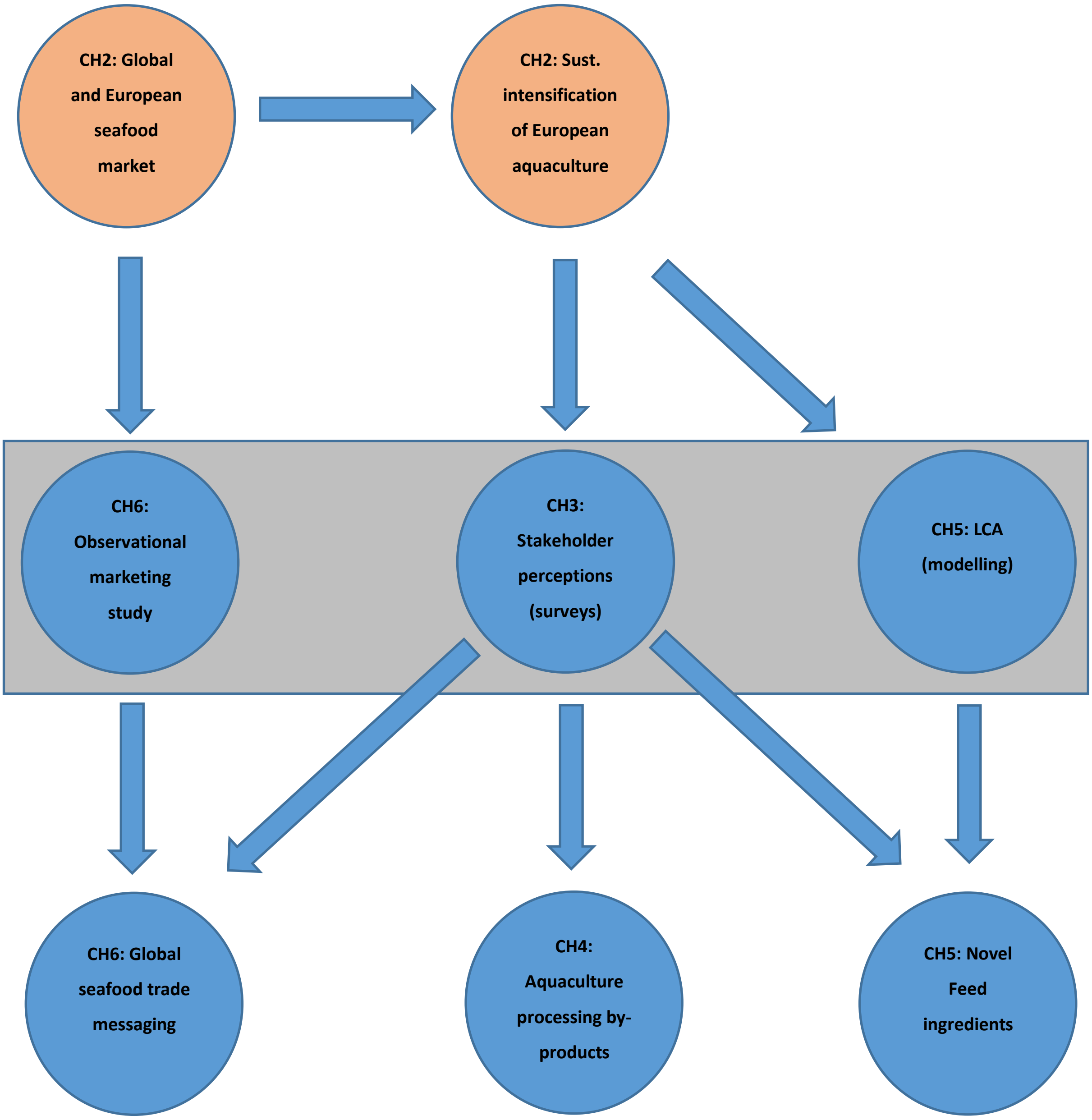


Figure 1.4: Research pathways into the respective Chapters (CH) in blue, literature review in orange, main methodologies in grey. The main findings are discussed in the final chapter (CH7).

CHAPTER 2: THE EUROPEAN SEAFOOD MARKET

Manuscript in preparation for the journal "*Reviews in Aquaculture*".

2.1 Introduction

Global seafood production (aquaculture and capture fisheries) reached 214 million MT in 2020. Aquatic animals represented 178 million MT, while algae comprised the remaining 36 million MT (FAO, 2022c). Asia is by far the largest seafood producer, farming an estimated 112 million MT in 2020, a slight increase compared to 2019, while wild production slightly decreased to 48 million MT (EUMOFA, 2022). In 2019 the proportion of fishery stocks, within biologically sustainable levels, declined to 64.4% (FAO, 2022c), while global aquatic food (excl. algae) consumption is increasing with an average annual rate of 3 percent since 1961 (FAO, 2022c). Consequently, driving aquaculture production of aquatic animals (excl. algae) to an estimated 87.5 million MT, which is approx. half of the aquatic animal supply in 2020 (FAO, 2022c). In contrast, in the case of the EU, three quarters of its seafood supply finds it origin from (import) capture fisheries. This is reflected by the five most popular species and their apparent consumption in the EU, such as tuna (13%), Atlantic salmon (10%), Alaska pollock (7%), cod (7%) and shrimps (6%), while the self-sufficiency rate for these species combined was 11% in 2020 (EUMOFA, 2022). Tuna is mixture of skipjack (*Katsuwonus pelamis*), yellowfin (*Thunnus albacares*), albacore (*Thunnus alalunga*), bigeye (*Thunnus obesus*), bluefin (*Thunnus thynnus*) and miscellaneous, while shrimp is a mixture of warmwater shrimps, cold-water shrimps, deep-water rose shrimps, shrimp *Crangon spp.* and miscellaneous shrimps. From these five popular species (groups) only a tiny proportion of shrimp (mostly warmwater shrimps) and Atlantic salmon is farmed in the EU (EUMOFA, 2022), while the tuna fattening sector is defined by many as value-added fisheries according to Benetti *et al.* (2016).

EU Atlantic salmon production decreased significantly, because of the UK leaving the EU at the beginning of 2020 (EUMOFA, 2022), as shown in Figure 1.2. Most of the EU Atlantic salmon production takes place in Ireland, but volumes are low, while EU demand is high. Consequently, EU self-sufficiency ratios for Atlantic salmon were very low (2%) in 2020, indicating a high dependency on the Norwegian (EEA) aquaculture industry. More specifically, the import of salmonids (97% Atlantic salmon, 3% trout and other salmonid species) into the EU was the highest of all species, representing 17% of total volume of extra-EU imports of aquaculture and fishery products in 2021 (EUMOFA, 2022). The UK also produces bivalves, but volumes are relatively low and therefore this did not have a significant effect on the EU bivalve supply, compared to the impact on the supply of EU Atlantic salmon (Figure 1.2). More specifically, mussels, which make up 5% of the EU apparent consumption show a healthy self-sufficiency ratio of 80% in 2020. Shrimp is also a popular product, mainly Argentine red shrimp (*Pleoticus muelleri*) and farmed warmwater shrimps (*Penaeus monodon and Litopenaeus vannamei*) in the EU, but self-sufficiency rates are as low as 12%. The supply is met by an equal share of farmed shrimp, mainly imported from Ecuador, India, Thailand, Indonesia, Vietnam, and wild shrimp from Argentina and Greenland (EUMOFA, 2022).

Freshwater fish was responsible for only 4% of the apparent consumption in 2020, including farmed species such as trout, which covers 2% of apparent EU consumption. The self-sufficiency rate for trout is as high as 86% in 2021 due to farmed production in France, Italy and Denmark, which produced more than half of the EU volume (EUMOFA, 2022). Aquaculture production of carp in Poland, the Czech Republic, and Hungary is mainly destined for the domestic market (EUMOFA, 2022). However, this commodity group also includes imported farmed freshwater fish, such as tilapia and pangasius, which shows potential to substitute white fish imports from capture fisheries (Little *et al.*, 2012). Whitefish is one of the largest segments in the seafood market and also includes capture fisheries species, such as Alaska pollock, cod, hake (European hake; *Merluccius merluccius*) and saithe (*Pollachius virens*), as well as aquaculture species, such as European seabass and tilapia (*Oreochromis niloticus*). Tilapia is produced globally, while most of the pangasius production is concentrated in the Mekong Delta in Vietnam, both produced in large volumes at competitive prices (Asche, Roll and Trollvik, 2009). Despite their affordability on the European market, Western NGOs and consumer groups criticized pangasius production systems, in terms of social and environmentally unsustainable practices, in combination with media coverage and industry generalization on e.g., “toxic food” (Newton *et al.*, 2019; Little *et al.*, 2012). This was partly incentivized by European producers of white fish (capture fisheries and aquaculture), who saw cheap pangasius imports as a threat (Little *et al.*, 2012). Over the years pangasius consumption within the EU declined significantly to less than 20% of its historical peak (Turenhout *et al.*, 2022). However, the sanctions on the Russian whitefish industry (e.g., pollock and cod), might create opportunities for Vietnamese pangasius to fill the supply gap (IntraFish, 2022). A steady supply of imported whitefish to produce added value seafood in Europe is considered a key factor to expand and maintain employment and trade opportunities (Turenhout *et al.*, 2022).

2.2 The aquaculture industry

2.2.1 EEA aquaculture species portfolio

Global aquaculture production in 2017 covered 425 species (Naylor *et al.*, 2021; FAO, 2021), while freshwater aquaculture accounted for 76% of the global edible aquaculture production (excl. aquatic plants) (Belton *et al.*, 2020). In contrast, while the EEA aquaculture industry produced 120 species of shellfish, algae, seaweed and aquatic animals in 2021, its farmed production of 2.87 million MT is dominated by 3 marine finfish (63.5%) 5 bivalves (19.1%) and 2 freshwater finfish species (12.4%) species (Figure 2.1, based on FAO data (2023b)). In terms of value, marine fish makes up 73%, while bivalves make up only 9.6%, which is half compared to its share in total farmed production (Figure 2.1 (FAO, 2023b)).

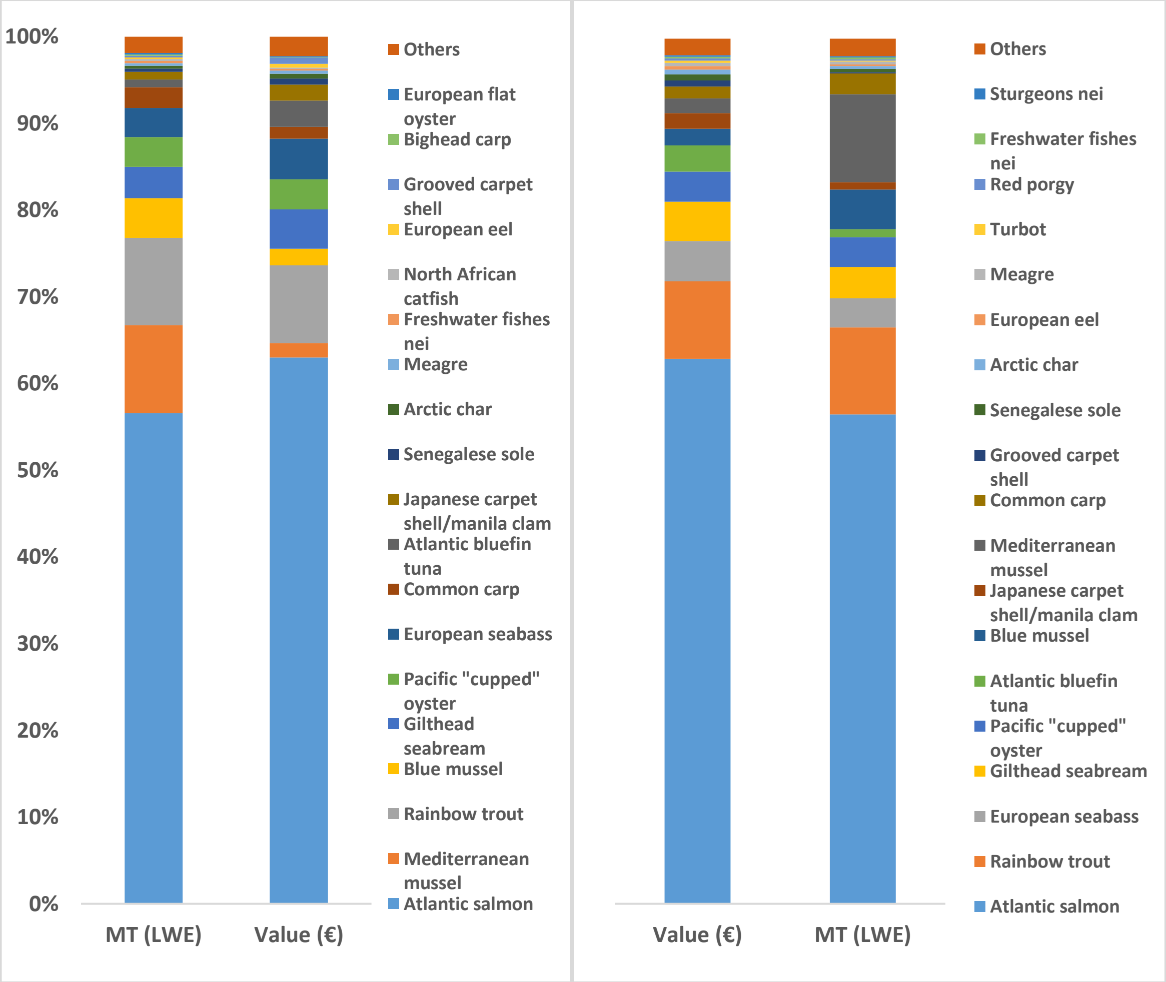


Figure 2.1: a) EEA aquaculture species sorted by weight (MT, LWE) and b) value (€) for the year 2021 with a total production of 2.87 million MT and €12.54 billion. "Sea mussels nei" covers a mix of Mytilidae species, including the blue and Mediterranean mussels, while "freshwater fishes nei" covers a mix of freshwater species not elsewhere included.

Marine (fed) species clearly dominate the EEA aquaculture species portfolio (FAO, 2023b). While the global demand for these species is expected to grow (FAO, 2018), EU apparent consumption patterns show a diversified preference towards different seafood species, mainly originating from capture fisheries (EUMOFA, 2022). While marine fed, such as Atlantic salmon, gilthead seabream and European seabass cover approx. 56%, 4% and 3% of EEA aquaculture production (FAO, 2023b), they cover only 10%, <1% and <1% of the apparent EU consumption in 2020, respectively (EUMOFA, 2022). Tuna is the most popular EU species covering 13% of total apparent consumption, but showing a low self-sufficiency rate of 28% (EUMOFA, 2022). Additionally, the EU bluefin tuna fattening industry is hard to categorize as it takes place at the intersection between capture fisheries and aquaculture (Benetti, Partridge and Stieglitz, 2016). More specifically, it shows a high dependency on capture fisheries for the supply of wild caught tuna juveniles, as well as for the feed supply in the form of large quantities of small pelagic fish, such as sardines and mackerel (Benetti, Partridge and Stieglitz, 2016). Consequently, facing significant sustainability challenges and uncertainties. Other popular capture fisheries and import species, such as cod and shrimps with low self-sufficiency rates, could be partly substituted by domestically farmed cod, whiteleg shrimp and giant tiger prawn. However, EEA production volumes of these species at 350, 142 and 35 MT in 2021, respectively (FAO, 2023b), are insufficient to supply domestic European demand. A larger share of European seafood supply could be sourced from EEA aquaculture production. However, European aquaculture is lacking scale, and growth capacity is undermined by cheaper alternatives from capture fisheries and (aquaculture) imports. This economic reality was also acknowledged by the FAO, emphasizing that a significant proportion of seafood is traded, which affects domestic markets and exposing local fishers as well as fish farmers to competition from imports (Asche, 2015; FAO, 2010).

2.2.2 Economic contribution

The EEA aquaculture sector produced an estimated 2.6 million MT with a value of €10.41 billion by 15,633 aquaculture enterprises employing 67,091 people (42,185 FTE) in 2020. Data on the total value of European aquaculture was obtained from the FAO (2023b) and converted based on average dollar to euro rate in 2020 (ExchangeRates, 2023).

The EU accounts for 14,229 and Norway and Iceland for 1,404 aquaculture enterprises (STECF, 2023; EUROFISH, 2021; StatisticsIceland, 2023) in 2020. The amount of enterprises is relatively low (1348) for Norway with a high aquaculture production volume, which can be explained by consolidation of the industry in the last decades (Asche *et al.*, 2013). The majority of the aquaculture enterprises in the EU are considered micro with less than 10 employees (STECF, 2023). It is estimated that 49% of the EU enterprises belong to freshwater aquaculture, 47% to shellfish, while only 4% of all enterprises are active in the marine sector in 2020 (STECF, 2023). More details on the economic contribution of European aquaculture species are discussed in depth in section 2.3.3.2.1 till 2.3.3.2.6.

2.2.3 Key value chain nodes for sustainable intensification

This section will cover the most important aquaculture value chain nodes for sustainable intensification. According to a study on value adding in the agri-food value chain by Cucagna and Goldsmith (2018) based on Humphrey and Memedovic (2006), the agri-food value chain is split in four main nodes: inputs, production, processing and delivery to consumers. Changes in consumer demand, development of complex food standards (safety and quality), technology advances and changes in industry structure have resulted in the downstream value chain being responsible for a significantly greater percentage of the final price paid by consumers compared to the upstream value chain. More specifically, in terms of the global agricultural markets, post-farm gate stages represent 84% of the food value, while 16% is supplied by the input and production stages (Humphrey and Memedovic, 2006; Goldsmith *et al.*, 2002). The share (%) of up- and downstream generated food value for aquaculture is expected to be variable and relatively unknown. However, it is expected that the downstream value chain is responsible for greater percentage of the food value paid by consumers (personal communication, Prof. Jimmy Young (2023)). Therefore, it should be a priority to explore the utilisation of fish by-products, as these readily available resources makes up half of the fish, such as heads, frames, trimmings, skin, viscera and blood (Stevens *et al.*, 2018). A re-evaluation of the potential to increase the supply of marine ingredients from under-utilised by-product resources has received far less attention, while this could benefit the resource efficiency both upstream as well as downstream (Figure 1.3). More, specifically, one third of the EPA+DHA originating from wild and farmed fish globally is discarded (Hamilton *et al.*, 2020) and fish by-products are “underutilised” in Europe (Jackson and Newton, 2016). By-products should be prioritised for human food consumption from a nutritional efficiency, food security and economic perspective, increasing the supply, without an increase in production volumes or the use of additional resources (Stevens *et al.*, 2018), a perfect example of sustainable intensification.

When food grade requirements are not met, fish processing by-products could function as low environmental footprint feed ingredients for Europe's livestock and aquaculture sectors, reducing the need for marine ingredients from whole fish and their (plant) substitutes. As feed application covers most of the cost and environmental impact of fed aquaculture production (Bohnes *et al.*, 2018; Rana, Siriwardena and Hasan, 2009), a higher inclusion of (fish) by-products, as well as other suitable novel feed ingredients, could improve the economic and environmental sustainability of the aquaculture industry. Therefore, the following sections will discuss the up- and downstream key value chain nodes for sustainable intensification in Europe, such as the aquafeed industry, the key aquaculture species, and their production system, as well as the fish processing industry.

2.2.3.1 Aquafeed

Feed provisioning is a crucial component in the sustainable aquaculture intensification process for most fish species (Little *et al.*, 2018). In general, feed input is responsible for more than 50 percent of the production costs (Rana, Siriwardena and Hasan, 2009), while it is also responsible for the majority of environmental impact of fed aquaculture production (Bohnes *et al.*, 2018). For the purpose of this thesis, I focussed on the feed application in the grow-out, while acknowledging the importance of the use of live feed and recently developments to apply artificial feed in the hatchery phase (Conceição *et al.*, 2010). Aquaculture feed for the grow-out stages ranges from dry commercially formulated pelleted feeds to the use of supplementary farm made feeds (Tacon and Metian, 2015). The latter is more applicable to less intensively produced common carp, where natural food organisms in the pond are supplemented with unprocessed natural cereals (Raftowicz-Filipkiewicz, 2013; Raftowicz and Le Gallic, 2019), while most of the production of Atlantic salmon, rainbow trout, gilthead seabream, European seabass, common carp and turbot in Europe receive formulated diets that are nutritionally complete. Norwegian Atlantic salmon and trout cover almost 67% of EEA farmed fish production in 2021 (FAO, 2023b), while consuming approx. 1,976,709 MT and 116,990 MT (WW) of feed ingredients, respectively (Aas, Åsgård and Ytrestøyl, 2022a). Atlantic salmon feed was produced by four companies, namely Biomar, Cargill, Skretting and Mowi, while the latter was not involved in the production of trout feed (Aas, Åsgård and Ytrestøyl, 2022a). However, feed production in the Mediterranean for species like rainbow trout, European seabass, gilthead seabream and turbot is much more fragmentated in countries like Spain, Greece, France, Italy, while Turkey also plays an important role in the provision of aquafeed (Fernández and Basurco, 2005). However, this data is from 2001 and the combined production of European seabass and gilthead seabream in the EU has almost doubled in the past 2 decades (FAO, 2023b).

Most farmed fish species in Europe are carnivorous, showing a dependency on marine ingredients, such as FM/FO (Naylor *et al.*, 2021). Marine ingredients, such as FM/FO, are crucial ingredients, stimulating senses, consumption and digestibility, while providing essential macro- and micro-nutrients (Glencross, 2020; Newton *et al.*, 2022). More specifically, FM/FO cover 12.1%, 10.3% and 13.4%, 10.8% of the average Norwegian salmon and trout feed in 2020, respectively (Aas, Åsgård and Ytrestøyl, 2022a). However, European seabass and gilthead seabream favour relatively higher inclusions of FM (15-20%) compared to FO (2-5%) in their diets, according to Seafish (2023a; 2023b), based on personal communication with IFFO. FM in turbot diets can be as high as 50%, as it is a highly carnivorous fish (Hoerterer *et al.*, 2022).

FM/FO are produced from small wild-caught pelagic fish, and from an increasing share from processing waste from fisheries and aquaculture (FAO, 2018; WorldBank, 2013; Pelletier *et al.*, 2018). An average of 33% of global FM and 26% of the global FO production originated from by-products between 2009 and 2013 (Jackson and Newton, 2016). More specifically, Europe played an important role, being the largest producer of FO, and second largest producer after Asia (excl. China) of FM from by-products. FO and FM production from by-products accounted for 90,000 MT and 381,000 MT, representing 47% and 54% of their total production of these ingredients on average between 2009 and 2013, respectively (Jackson and Newton, 2016). In this time, approx. 1.5 million MT of raw materials originated from whole fish. Most of the by-products were sourced from wild capture (approx. 1.17 million MT), while aquaculture by-products only accounted for 331,000 MT (Jackson and Newton, 2016).

In 2019 the proportion of fishery stocks, within biologically sustainable levels declined to 64.4% (FAO, 2022c). A growing demand for seafood, and finite supply of marine ingredients (price and sustainability concerns) has resulted in feed manufacturers decreasing the inclusion level of FM and FO (Naylor *et al.*, 2009; Pelletier *et al.*, 2018; Froehlich *et al.*, 2018). Consequently, shifting towards crop-based ingredients (Pelletier *et al.*, 2018; Froehlich *et al.*, 2018; Gatlin *et al.*, 2007), such as high levels of soy protein (20.9%) and rapeseed oil (18%) in Atlantic salmon diets (Aas, Åsgård and Ytrestøyl, 2022a). While FM and FO have environmental concerns, this is also the case for their substitutes, such as plant derived meals and concentrates (Newton and Little, 2018; Blanchard *et al.*, 2017; Malcorps *et al.*, 2019a). Globally, agricultural land is under pressure by the increasing demand for food, feed, biofuels, biobased materials (Spiertz and Ewert, 2009; Godfray *et al.*, 2010), and the effects of climate change (FAO, 2018; Fry *et al.*, 2016). The global food system is also the primary driver of biodiversity loss (Benton *et al.*, 2021). According to the FAO (2020e), approx. 38% of global land surface is considered agriculture (approx. 5 billion ha), from which a third is cropland and two-thirds is used for livestock grazing (meadows and pastures) (FAO, 2020e). However, if pastures and animal feed production is considered, it is estimated that 77% of agricultural land area is used for livestock (Ritchie and Roser, 2019). The production of ruminants (e.g., cattle and sheep) requires mainly grazing land, while the increased production of non-ruminants, such as pigs and poultry requires also arable land, freshwater and nutrients (fertilizer) for feed production (Galloway *et al.*, 2007). However, estimates from the last decade, highlighted that 91% (4.9 billion ha, equal to approx. 40% of total global land surface) of the total 5.41 billion ha of available suitable agricultural land is occupied (incl. pasture) (Zabel, Putzenlechner and Mauser, 2014; FAO, 2014; Popp *et al.*, 2017). Consequently, indicating that horizontal agricultural expansion is limited and mostly at the expense of other land use (e.g., forest or protected areas) with social and environmental implications (Zabel, Putzenlechner and Mauser, 2014).

Agriculture activities are also responsible for use of 70% of the freshwater resources, potentially leading to water scarcity in the future (Salin *et al.*, 2018). Additionally, there are concerns in regards to nutrients with limiting supply applied in food production, such as the use of phosphorus (Ytrestøyl, Aas and Åsgård, 2015; Roy *et al.*, 2016; Kraan, 2010), while it's use in fertilizers combined with nitrogen leads to eutrophication and dead zones in coastal marine ecosystems (Pelletier *et al.*, 2018; Kraan, 2010; Diaz and Rosenberg, 2008). The production of ruminants (e.g., cattle and sheep) requires mainly grazing land, while the increased production of non-ruminants, such as pigs and poultry requires arable land, freshwater and nutrients (fertilizer) for feed production (Galloway *et al.*, 2007). Agricultural production to satisfy the demand for aquafeed ingredients, such as rapeseed, soybean, corn, nuts and wheat, was estimated at 10 million ha (approx. the size of Iceland in 2008) (Fry *et al.*, 2016), while water demand was estimated between 31–35 km^3 (Pahlow *et al.*, 2015). This is especially relevant for EEA aquaculture, despite their relatively small share (approx. 2.3%) in global aquaculture production in 2021 (FAO, 2023b), as their species portfolio is highly dependent on imported marine and terrestrial ingredients (Newton and Little, 2018).

Marine ingredient substitution with plant ingredients could also compromise health and welfare of the cultured animal (Rana, Siriwardena and Hasan, 2009; Saito *et al.*, 2020), and micro- and macro nutrient levels in the final consumed product (Sprague, Dick and Tocher, 2016; Nichols *et al.*, 2014; Saito *et al.*, 2020). More specifically, FO is rich in n-3 LC-PUFA, but its replacement in salmon diets with vegetable oils (richer in n-6 PUFA) over the past decades has resulted in a change in salmon's fatty acid composition. These trends highlight the implications of reducing marine ingredients in the aquaculture diet in terms of the quality of the final product for human consumption (Sprague, Dick and Tocher, 2016). While some novel feed ingredients, such as insects or microalgae show potential to be included in fish diets, (consistent) nutritional quality, availability, price (Pelletier *et al.*, 2018; Hua *et al.*, 2019), as well as environmental performance (Maiolo *et al.*, 2020b), remains a challenge. This is reflected by its low industrial use, where insect meal, microalgae, fermented products and single cell protein made up only 0.4% of the diets for Atlantic salmon and trout in Norway in 2020, according to Aas *et al.* (2022a; 2022b).

Europe is highly dependent on imported feed ingredients (Newton and Little, 2018). However, a dependency on imported ingredients makes the industry vulnerable to external (economic) shocks and therefore less resilient (Troell *et al.*, 2014). The share of by-products in FM and FO production is rising by an average of 1-2% per year globally (Shepherd and Jackson, 2013; Jackson and Shepherd, 2012). Including relatively "low economic value" fish by-products in aquafeed reduces the demand for wild-caught pelagic fish, consequently, resulting in a lower FIFO, creating environmental and economic incentives to utilise by-products (Kok *et al.*, 2020). Europe has a dominant role in the production of marine ingredients from fish by-products, but most of the raw materials find their origin from capture fisheries (Jackson and Newton, 2016). It is important to re-evaluate the potential to increase the supply of marine ingredients from under-utilised aquaculture processing by-products. This would reduce the dependency on feed ingredient imports and capture fisheries. Additionally, it would reduce the need for marine ingredient substitutes, such as plant ingredients, which affects the nutritional value (EPA+DHA) of the final aquaculture product (Sprague, Dick and Tocher, 2016) and associated environmental impact (Newton and Little, 2018; Blanchard *et al.*, 2017; Malcorps *et al.*, 2019a). Marine ingredients provide essential nutritional benefits (Glencross, 2020; Newton *et al.*, 2022), while their LCA impact is typically lower than terrestrial ingredients (Newton *et al.*, 2022). They could play a crucial role in the sustainable intensification of European aquaculture.

2.2.3.2 Key species and production systems

Bivalves (e.g., clams, mussels and oysters) cover approx. 20% of EEA aquaculture production in 2021 (FAO, 2023b). Their production is characterized by low resource intensity in the natural marine environment (Willer, Nicholls and Aldridge, 2021; Costello *et al.*, 2020; Willett *et al.*, 2019; Willer and Aldridge, 2020). However, while their production is considered sustainable, demand is low (Willer, Nicholls and Aldridge, 2021), limiting its current potential to support the sustainable intensification of European aquaculture. Therefore, for the purpose of this thesis, the sustainability potential of the main finfish and a flatfish species are discussed due to their relatively fast-growing consumer demand. They show potential for sustainable intensification, mainly through increased processing and strategic utilisation, improving the sustainability of animal feed provisioning in Europe as well. There is a focus on the grow-out phase, being a hotspot for sustainability, as most of the feed is applied during this stage.

2.2.3.2.1 Bivalves

Bivalve production was approx. 547,451 MT (approx. €1.12 billion) in 2021, which is approx. 20% of the total aquaculture production by LWE in the EEA (Figure 1.2a-b). Shellfish aquaculture production in Norway and Iceland is low, but significant in the EU where it represents 6,183 enterprises employing 40,620 employees (16,947 FTE). More specifically, France (2,214 enterprises and 14,823 employees (8,118 FTE)), followed up by Spain (2,210 enterprises and 14,520 employees (6,058 FTE)), Italy (398 enterprises, 6,848 employees (1,823 FTE)) and Portugal (654 enterprises, 740 employees (475 FTE)) were the most important EU shellfish aquaculture production countries in 2020 (STECF, 2023).

The most important European cultivated bivalve species are blue and Mediterranean mussels, Pacific cupped oyster and the Japanese carpet shell/manila clam (FAO, 2023b). Spain, France, and Italy are the largest bivalve producers, in which mussels and the Pacific cupped oyster dominate the species portfolio. However, the actual supply of bivalves is overestimated in direct comparison with finfish, as FAO statistics report wet weight equivalents (including inedible shell) (Edwards *et al.*, 2019; Belton *et al.*, 2020). While the edible yield of bivalves can vary between e.g., mussels (61%) and oysters (16%) (Fry, 2012), it averages at 17% (Edwards *et al.*, 2019; Belton *et al.*, 2020). This is significantly less compared to the edible yield of finfish (87%; (Edwards *et al.*, 2019; Belton *et al.*, 2020)). Additionally, most bivalves are consumed fresh at home, which is a limiting factor for collection of shells (Alonso, Álvarez-Salgado and Antelo, 2020). Consequently, reducing its potential to be used in industrial applications, such as fertilizer, filters and building material (Summa *et al.*, 2022).

Most of the EEA bivalve production takes place in the marine environment, but approx. 5% is produced in brackish water in 2021. Brackish water production includes approx. 94% of Japanese carpet shells, 42% of the *corrugated venus* and 27% of the common edible cockles, while these values for other bivalve species, such as the European flat oyster, Pacific cupped oyster and grooved carpet shell, are neglectable (FAO, 2023b). Bivalves show interesting nutritional characteristics, and their production does not require large amounts of terrestrial resources, such as feed, freshwater and land (Costello *et al.*, 2020; Willett *et al.*, 2019; Willer and Aldridge, 2020). Additionally, environmental benefits are associated with its production, such as carbon sequestration, nutrient removal, coastal protection and increased biodiversity (Olivier *et al.*, 2020). However, production is challenged by multiple factors, such as low consumer demand and limited availability of convenience products, food safety concerns and production efficiencies (Willer, Nicholls and Aldridge, 2021). The latter might explain the low profitability of the EU mussel sector (Avdelas *et al.*, 2020), while the decrease in economic performance might also have been affected by added competition from Chilean mussel imports lowering prices in the EU market (Salazar and Dresdner, 2022). Additional challenges are lack of seed (spat) and disease. Altogether, leading to an overall decline in EU production in the past two decades, contrary to global mussel production which actually increased (Avdelas *et al.*, 2020).

2.2.3.2.2 Atlantic salmon

EEA aquaculture production of Atlantic salmon accounted for approx. 1.62 million MT (Figure 1.2), estimated at €7.90 billion in 2021. The aquaculture sector in Norway and Iceland is covered by 1,348 and 56 enterprises, 9,975 and 523 employees in 2020, respectively, most of them active in the production of Atlantic salmon (EUROFISH, 2021; StatisticsIceland, 2023). The FTEs for Norway and Iceland are estimated at 7,225 and 379, respectively, based on the employment data from EUROFISH (2021) and StatisticsIceland (2023) and the calculated average (72%) FTE of total employment in the EU from STECF (2023).

Norway is by far the largest producer (FAO, 2023b), but the domestic market of 5 million people is small and therefore It exports 95% of its supply to more than 100 countries (Straume *et al.*, 2020; Straume, Landazuri-Tveteraas and Oglend, 2020; Cojocaru, Iversen and Tveterås, 2021). The UK produced approx. 203,881 MT Atlantic salmon in 2019, but in 2020 this volume was not part of the EU internal market anymore because of Brexit. Consequently, resulting in a decline in overall EEA aquaculture production (Figure 1.2a). Atlantic salmon production in Ireland was performed by 28 enterprises, employing 212 people in 2020 (159 FTE) (STECF, 2023), while these statistics for Denmark, France and others are neglectable.

Norwegian Atlantic salmon saw a rapid growth from 50 MT in 1970 to 1.56 million MT in 2021 (FAO, 2023b), and this supply chain is considered the most developed, vertically integrated and industrialised compared to most other farmed species (Asche, Cojocaru and Roth, 2018). This has resulted in highly geographically concentrated production of Atlantic salmon, in which Norway produced approx. 54% of the global supply, followed up by Chile (25%), UK (7%), Canada (4%), Faroe Islands (4%) and others (6%) in 2021 (FAO, 2023b). Two important factors have contributed to the growth and development of the Norwegian industry, such as the increase in farm and company size (Asche *et al.*, 2013). Norwegian salmon aquaculture started in the 1950s with a range of production methods to produce Atlantic salmon and rainbow trout adopted from the European trout industry (Asche and Bjørndal, 2011; Landazuri-Tveteraas *et al.*, 2021; Hersoug, 2021). In the 1970s sea pens were introduced (Afewerki *et al.*, 2022; Isabella and Hunt, 2020) showing potential to grow the industry. However, production volumes were capped by a regulatory system established in 1973, which was initially designed to support coastal communities, but prioritised environmental sustainability over time (Osmundsen *et al.*, 2021; Hersoug, 2022; Aslesen, 2007). More specifically, production was limited by the volume of the sea pens, while ownership was restricted to one farm. However, from 1989, this regulation was only applicable to a depth of 5 meters, creating incentives to develop deeper sea pens (Hersoug, 2021). While the smolt production was indoor land-based (flow-through system) since the 1980’s (Sandvold, 2016), grow-out farms moved further out to see as a result of the increase in dimensions of sea pens. More specifically, from 5-10m in diameter and 4m deep to an average of >50 meter in diameter and 40m deep, from 1970 till today, respectively (Afewerki *et al.*, 2022; Isabella and Hunt, 2020). Consequently, farms were not directly accessible by land and therefore feeding barges were added for personnel and to store (feed) equipment. This enabled companies to locate their farms on exposed locations with more favourable conditions, such as superior water quality, oxygenation, and lower sea lice levels, favouring growth (Afewerki *et al.*, 2022). The trend of moving the farms to more exposed sites was accelerated by increased environmental regulations, especially in the 1990s (Berge and Norsk, 1998).

New “economies of scale” were unlocked in 1992, as a result of a change in regulations that previously restricted a farmer to one license (Afewerki *et al.*, 2022). To operate an Atlantic salmon or trout farm at a certain location, a license is required (Sund, 2021; Asche *et al.*, 2013). However, over time, production per license increased from 26 MT to 1130 MT from 1980 to 2010, respectively. As described previously, production limits were based on pen size, while since 2004 each license represents a maximum allowable biomass. Nevertheless, the change in regulations enabled companies to operate more than one license at a farm and therefore scaling production, if the environmental carrying capacity allowed (Asche *et al.*, 2013; Afewerki *et al.*, 2022). This led to company growth through industry consolidation, resulting in a decrease in companies from approx. 70 in 1997 to less than 20 in 2012, responsible for 80% of Norwegian production (Asche *et al.*, 2013). Some larger companies had access to more resources, such as capital through the Norwegian stock exchange, while at the same time economies of scale, capacity in R&D, innovation, sales and marketing were important contributors to the growth of the industry in the last decades (Asche *et al.*, 2013).

Industry growth is currently limited by environmental regulations (e.g., sea lice and escapees) limiting the access to new production licenses and locations (Abolofia, Asche and Wilen, 2017; Torrissen, Jones and a., 2013; Osmundsen *et al.*, 2022; Afewerki *et al.*, 2022). Growth is also limited by temporary halt on permit applications for new land-based fish farms. This was done to further develop and modernise regulations of projects using sea water (FishFarmingExpert, 2022). Additional limits to growth are a recently introduced corporate tax increase from 22% to 40% (TheFishSite, 2022).

The use of large quantities of feed, especially in unsuitable locations could result in the accumulation of excessive nutrients under the farm potentially affecting benthic communities (Buschmann *et al.*, 2006; Kuttia, Ervika and Høisæter, 2008; Bannister *et al.*, 2014). Additionally, salmon lice is still considered one of the major challenges for the industry (Torrissen *et al.*, 2013). To a certain extent, salmon lice from farms also negatively impacts wild stocks of salmonids, while there are also concerns regarding the resistance of salmon lice against commonly used drugs treatments for both farmed as well as wild fish. Vaccines along other antiparasitic measures are considered a promising strategy, also for salmon escapees with limited ability to spread lice among the wild population (Torrissen *et al.*, 2013). However, additional concerns regarding escapees remain, such as interbreeding and competition and spread of disease to wild salmon (Naylor *et al.*, 2005; Jensen *et al.*, 2010). In response to these challenges, some of the larger companies are now exploring new offshore farming locations, semi-enclosed sea-pens, as well as production salmon in land-based recirculation systems (Føre *et al.*, 2022; Øvrebø *et al.*, 2022). These developments are supported by specialised companies focussing on the development of equipment, technology, maintenance, and logistics in collaboration with fish farmers and researchers (Tveteras, 2002). It is suggested that lower tax for the salmon industry and allocation tax revenues from the oil and gas industry to the salmon industry could support growth and innovation (TheFishSite, 2022).

2.2.3.2.3 Rainbow trout

The EEA produced 30% of the global farmed rainbow trout production (952,691 MT) in 2021, followed by the Islamic Republic of Iran (20%) and Turkey (17%) (FAO, 2023b). Rainbow trout is the largest freshwater farmed species in Europe (FAO, 2023b). Over the last 3 decades rainbow trout production in the EEA has fluctuated between approx. 200,000-300,000 MT, while in 2021 it accounted for 288,877 MT (approx. €1.12 billion) (FAO, 2023b). Norway’s marine production accounted for approx. 33%, while the rest was produced in the EU in a mix of freshwater and marine aquaculture production systems (FAO, 2023b). Within the EU, the trout aquaculture sector was represented by 2,422 enterprises, employing 8,223 people (5,553 FTE) in 2020 (STECF, 2023). Production in 2021 took place in 24 EU countries, in which Italy, France, Denmark, Poland, Spain and Finland were the largest producers.

Approx. 40% of the rainbow trout production is marine aquaculture, while 60% is produced in freshwater aquaculture systems, which makes rainbow trout the largest freshwater farmed fish in Europe (FAO, 2023b). Freshwater culture consist mostly of flow-through systems in the form of tanks and raceways, as well as recently developed recirculating aquaculture systems in Denmark (Bostock *et al.*, 2016). These systems focus mainly on the production of smaller size (portion) fish in the range of 200-300g (EUMOFA, 2021b). Contrary, marine cage farming produces mostly larger-sized trout (EUMOFA, 2021b). This type of trout is defined as steelhead trout with a relatively small market, but it is gaining popularity in countries like the USA (SupermarketPerimeter, 2020).

2.2.3.2.4 Gilthead seabream and European seabass

For purpose of this thesis, both species are discussed in the same section, because aquaculture production takes place in similar production systems (Sánchez, García and Luna, 2020; FAO, 2023a; FAO, 2023f; Ferreira *et al.*, 2010; Yúfera and Arias, 2010). Global production of gilthead seabream and European seabass was 319,215 MT and 299,810 MT in 2021, in which Turkey, Greece and Egypt produced approx. 42%, 21%, 13% and 52%, 17%, 11%, respectively (FAO, 2023b). The European production of gilthead seabream and European seabass accounted for 103,130 MT (approx. €0.57 billion) and 96,647 MT (approx. €0.59 billion) in 2021, respectively (Figure 1.2a). STECF (2023) estimated that the EU sector had an estimated turnover of €1.04 billion, by 600 enterprises, employing 5,912 people (5,153 FTE) in 2020. Gilthead seabream and European seabass are considered the most important farmed species in the Mediterranean (STECF, 2023; Llorente *et al.*, 2020), where most of the European aquaculture production takes place. A relatively small European production volume can be found on the Atlantic side of France, Portugal and Spain (FAO, 2023b).

Gilthead seabream production in the EU is dominated by Greece, Italy and Spain, while European seabass production is dominated by Greece, Spain and Croatia (FAO, 2023b). The majority of the production takes place in the marine environment, while a small fraction (approx. 2%) takes place in brackish water (FAO, 2023b). Marine production is dependent on feed production, which was identified by Kallitsis *et al.* (2020) as the most environmental impact intensive process. On a live mass basis, seabass had relatively lower environmental impacts, but the environmental impact was lower for gilthead seabream when compared on a protein basis (Kallitsis *et al.*, 2020).

Gilthead seabream show a preferences for feed lower in the food chain, compared to seabass, which is more carnivorous (FAO, 2023a; FAO, 2023f). More specifically, due to their different feeding characteristics, a small proportion of the total production is farmed in polyculture in lagoons, which are naturally stocked with fry of both species (among others such as mullets and eels) using barriers to capture fish during their migration (FAO, 2023a; FAO, 2023f). Polyculture is also an established practice in earthen (semi-intensive) pond production, which are considered the main production systems for European seabass and gilthead seabream (proportion 4:1, respectively) in Portugal and Southern Spain. In these systems, gilthead seabream is used to control macroalgae growth, while the carnivorous nature of European seabass is used to control other small fish species entering and competing for feed in the pond (Ferreira et al., 2010). Most of these “polyculture” practices in e.g., Spain and Italy are considered traditional (Yúfera and Arias, 2010; Sánchez, García and Luna, 2020). However, the development of new hatchery and rearing techniques in the 70s and 80s transitioned to more intensive methods of production. Consequently, a large proportion of the farmed gilthead seabream and European seabass is supplied by floating cages in the Mediterranean (Sánchez, García and Luna, 2020). It is estimated that 82% of the farms used sea cages, while 10% used land-based intensive tanks or raceways and 8% of the farms used semi-intensive earthen pond production systems (Muir and Basurco, 2000; François et al., 2010; Jawad, 2012).

In the last two decades the gilthead seabream and European seabass saw a rapid rise in supply. This was mainly caused by increase EU production, as well as imports, especially from Turkey. Increased supply in combination with limited market expansion affected the average market price of European seabass and gilthead seabream. Consequently, the industry has increased efficiency by consolidation, resulting in larger and more profitable companies (Rad and Köksal, 2000; Rad, 2007; Wagner and Young, 2009; STECF, 2023; Llorente et al., 2020). In the case of Greece, this has resulted in the merger of the three major producers into a large company group under the same ownership. This company also owns production companies in Spain. Consolidation was also observed in Italy where most of the production is controlled by three companies. An increase in offshore aquaculture production is expected from Portugal, as well as for Croatia which invested in value added processing to increase production efficiency and expand the product portfolio (STECF, 2023).

In the last decades, throughout Europe efforts were made to reduce production costs, as well as increasing the market demand for gilthead seabream and European seabass. This was supported by government and private company research and innovation investments (Llorente *et al.*, 2020; GLOBEFISH, 2017). This is crucial, because despite an increase in export to North America and the Middle East, most of the production is still consumed in Mediterranean countries (STECF, 2023). European producers still face economic disadvantages compared to their competitors, such as high labour costs, administrative obligations, such as licensing that increase cost of production (Koçak and Tatlıdil, 2004; Bozoglu and Ceyhan, 2009; STECF, 2016; STECF, 2018; STECF, 2023; Arikan and Aral, 2019; Fernández Polanco *et al.*, 2019). This highlights the importance of production efficiency improvements to increase the competitiveness between the domestic European producers, as well as with the Turkish producers (Llorente *et al.*, 2020). Additionally, produced in the EU labels could add value, emphasizing the importance of strictly regulated conditions and the differentiation from non-EU imported products (STECF, 2023).

2.2.3.2.5 Common carp

Europe produced more than 68,000 MT (approx. €175 million) of common carp in 2021 (Figure 1.2a), in which Czech Republic, Poland and Hungary produced approx. 26%, 26% and 17% (FAO, 2023b). Although on a global scale, this is marginal (approx. 2%) of the 4.2 million MT of common carp produced. However, common carp is the second largest European farmed freshwater species after rainbow trout (60% produced in freshwater) (FAO, 2023b). It is estimated that European freshwater aquaculture employed 20,626 people in 7,582 enterprises in 2018, a large part covered by countries with a significant stake in pond farming, such as Germany, Poland, Czech Republic and Romania, according to EUMOFA (2021a), based on DCF/EUMAP data (2023b). More specifically, the estimated amount of enterprises and employed people in freshwater aquaculture varies for Poland (1,050 and 6,262), Czech Republic (650 and 1,239) and Hungary (398 and 1,449) in 2018, respectively (EUMOFA, 2021a; DCF/EU-MAP, 2023a). Unfortunately, economic country data is not available on a cyprinid aquaculture level for some of the largest producers (e.g., Poland, Czech Republic and Hungary), but is estimated that this type of aquaculture is covered by 4,486 enterprises, employing 8,901 people (7,022 FTE) in the EU in 2020 (STECF, 2023).

Carp farming activities benefits the social and economic sustainability of rural areas, where most of the pond farming is located (EUMOFA, 2021a). Despite the stagnation of carp production in the last decade, it remains an important food for seasonal celebration (e.g., Christmas and Easter), when most of the carp is purchased alive or fresh (EUMOFA, 2021a).

Contrary to trout production, pelleted feed is not commonly applied in carp farming in Poland. Most of the carp production is considered “extensive” or “semi-intensive” (EUMOFA, 2021a), taking place in ponds covering a total estimated surface area between 53,800 ha (Lirski and Myszkowski, 2021), 60,000 ha (EUROFISH, 2020) up to 70,000 ha (10% of inland water bodies (Turkowski and Lirski, 2011)). Carp production cycles are long and take up to three years (Raftowicz *et al.*, 2020). Production is low in the “natural” extensive pond systems in Europe, estimated at a maximum of 500 kg of fish/ha/year, mostly common carp, but also roach (*Rutilus rutilus*), bream (*Abramis brama*), tench (*Tinca tinca*), pike (*Esox Lucius*) and pikeperch (*Sander lucioperca*). In these ponds carp feeds on natural growing food in the pond, in which carp growth can be stimulated by e.g., pond fertilization (EUMOFA, 2021a). This is considered semi-intensive and in addition supplementary feed and fry from hatcheries are introduced, allowing for higher stocking densities (EUMOFA, 2021a). Some studies find that supplementary feeding of unprocessed, natural cereals, benefits the taste and quality of the final product (Raftowicz-Filipkiewicz, 2013; Raftowicz and Le Gallic, 2019). For Poland yields ranged from 361 kg/ha to 731 kg/ha per production cycle (Lirski *et al.*, 2013), with an upper-limit of fish growth at 1,500 kg ha^{-1} year^{-1}, as defined by Polish law “*Ustawa z dnia 20 lipca 2017 r. - Prawo wodne [Water Law], (consolidated text Dz.U. 2017, item. 1566)* (KancelariaSejmu, 2017)”. Overall, in Poland, it is estimated that 90% of the carp are fed grains and 10% formulated feeds (Lirski, 2021b). These extensive and semi-intensive fish production practices are slightly different compared to Czech Republic, where it is estimated that 25-30% of the carp production finds its origin from supplementary feeding (Adámek *et al.*, 2012). They are produced in aquaculture production ponds covering an area of 52,000 ha, with pond size varying from 1 to 489 ha. The carp dominates pond production in Czech Republic, but other species, such as Chinese carps (grass carp (*Ctenopharyngodon idella*), bighead (*Hypophthalmichthys nobilis*) and silver carp (*Hypophthalmichthys molitrix*)), tench, as well as predatory fish, such as pike, pikeperch, European catfish (*Silurus glanis*) and perch (*Perca fluviatilis*) are also produced (Adámek *et al.*, 2012). In the case of Hungary, 28,000 ha is used as fishponds, in which common carp makes up approx. 70% of the total fish production farmed alongside other carp species (20%, incl. Chinese carp), other fish species (9%) and carnivorous fish (1%) (FAO, 2023d). In the case of Poland, other fish species in the common carp ponds does not exceed 12% (Lirski and Myszkowski, 2021).

Poland is one of the biggest common carp producer in Europe (FAO, 2023b), where most of the production is concentrated in the Barycz Valley (Lower Silesia Province), in which the "Milicz ponds" are considered the largest carp breeding centre in Europe (Raftowicz *et al.*, 2020). The total pond area in the Lower Silesia Province was estimated at 8,493 ha, covering 48 farming areas. A total of 6 farming areas are larger than 300 ha (covering 77% of total area) and 11 are considered medium-sized, covering 80-300 ha each. A total of 20 farming areas are considered small (10-80 ha), while a total of 11 are defined as micro (<10 ha) (Raftowicz and Le Gallic, 2019). Especially in the Barycz Valley, many of the ponds used today were originally built between the 11th and 17th century ("golden era" of Polish carp farming). However, as indicated by the study of Raftowicz and Le Gallic (2019), the surface area of the individual ponds has decreased over time. Nevertheless, they still cover a large area (7,500-8,253 ha) and are highly concentrated in the Barcyz Valley. This includes 26 fish farms, employing 271 people (Raftowicz, Kalisiak-Mędelska and Struś, 2020; CLLD, 2020; Raftowicz *et al.*, 2020). Based on the average farm area in the Barcyz Valley (7,877 ha) and the upper-limit of fish growth at 1,500 kg/ha/year, total production in 2020 is estimated at 12,000 MT, which is slightly more than 50% of the total production of 22,500 MT in Poland in 2020.

The carp ponds in Poland, in particular the majority of the ponds in the Barycz Valley, function as a natural protection area under the Natura 2000 (Raftowicz *et al.*, 2020), which is a network of protected natural habitats and rare and threatened species in the European Union (EC, 2023). The Barycz Valley is considered the largest nature reserve in Poland where the ponds function as ecosystem services, while they also contribute to cultural value and the region's identity (Lasner *et al.*, 2020). This enables farmers to interact with tourism, which is considered an appropriate strategy to increase the profitability of the industry, according to study of Raftowicz *et al.* (2019). However, ecological objectives do not always align with economics, which results in conflicts and challenges for the farmers. Firstly, common carp's long production cycle takes up to three years, in which they are fully exposed to protected piscivorous bird species, such as the grey heron, eagle, and black cormorant (Raftowicz *et al.*, 2020). Additionally, the sector is exposed to diseases (e.g., KHV virus), which can freely spread in the large ponds. Thirdly, carp farms are vulnerable to weather events leading to floods and droughts (Raftowicz *et al.*, 2020). Water shortages in this region are expected (Lasner *et al.*, 2020) and in the last few years Poland has experienced meteorological droughts (Kubiak-Wójcicka and Machula, 2020; Kubiak-Wójcicka and Bak, 2018). While climate change can intensify these events and negatively affect the sector (Panicz *et al.*, 2022), an overall increase in temperature can increase the appetite of carp, which can result in better feed uptake and consequently a higher volume output of the sector (Varga *et al.*, 2020). However, the study of Varga (2020) focussed on Hungary, did not take the effects on climate change on fish disease into account. Nevertheless, climate change can increase the vulnerability of the aquaculture farms (Panicz *et al.*, 2022), as well as its economic performance due to lower farming efficiency. This could favour imports of cheaper common carp products, which already makes up approx. 15% of carp sales in

Poland (Raftowicz *et al.*, 2019; Raftowicz *et al.*, 2020). The majority of the imports originated from Czech Republic (estimated at 80%, (Tyminska *et al.*, 2020; Raftowicz *et al.*, 2020)), while the rest was imported from Hungary, Lithuania and China (Raftowicz *et al.*, 2020; Raftowicz, Struś and Wodnicka, 2019).

The processing sector for domestic carp production is undeveloped. Hungary processed approx. 10-15% of its domestic fish production, while this was estimated at 8-10% in the Czech Republic (FAO, 2023c; FAO, 2023d). Regarding the latter, this was processed in 14 leading facilities and 25 smaller processing units. Only a few of these processing facilities comply with EU standards and are therefore able to export processed fish (FAO, 2023c). In the case of Poland, the majority of their fish processing facilities exclusively processed imported raw materials, mostly from marine origin (FAO, 2023e). Nevertheless, most carp in both the Czech Republic, Hungary as well as Poland are mostly being sold alive around Christmas or Easter (FAO, 2023d; FAO, 2023c; FAO, 2023e), while an increasing amount of carp in the Czech Republic is offered domestically in a processed form (FAO, 2023c). Around half of the domestic carp production is domestically consumed, the other half is exported to Germany and Slovakia, respectively. Consequently, making the Czech Republic the largest European exporter of carp (FAO, 2023c). This clearly distinguishes the Czech Republic common carp industry from Poland and Hungary, where most if the carp production is destined for the domestic market (FAO, 2023e; FAO, 2023d).

2.2.3.2.6 Turbot

Global turbot (*Psetta maxima*) farming accounted for 72,065 MT (approx. €33.33 million) in 2021, in which China produced approx. 95% (FAO, 2023b). Global production reached a peak between 2011-2013 and then slightly declined till 2015 (EUMOFA, 2018b), which is also observed on an European resolution. The decline of production lasted a few years followed up by an increase in Chinese production, while European production fluctuated and dropped in 2021. According to the FAO (2023b), the EU produced 10,470 MT in 2020 (Figure 1.2a), which is relatively close to the 7,000 MT estimated by STECF (2023) equal to €49 million, mainly produced in Spain and Portugal. In 2020, turbot was produced by a total of 11 companies in the EU, from which 2 are considered large, 1 medium-sized, 6 small and 2 micro. These companies can be found in France (3), Netherlands (1), Portugal (3) and Spain (4) (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022).

According to FAO data (2023b), Portugal (3,538 MT), the Netherlands (100 MT) and Italy (30 MT) were the only turbot farming nations left in Europe in 2021, producing approx. 5% of global production. Spanish production declined from 6,963 in 2020 to zero in 2021 according to FAO data (2023b), which is highly unlikely considering that approx. 85% of the Spanish farmed turbot supply is farmed by two large leading companies. This is the result of industry consolidation, resulting in a 60% decrease in the number of companies in Spain, while the number of employees remained stable

(Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022). Most of the turbot in the Netherlands is produced by a single company (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022). The large size of the companies in the Netherlands and Spain benefitted from economies of scale, technological innovation as well as trade agreements with large retailers and supermarkets, which benefitted the economic performance significantly (Fernández-González, Pérez-Pérez and Gil, 2020). In contrast, France produced an average of 840 MT between 2000 and 2008 and then the production dropped to zero, according to the FAO data (FAO, 2023b). However, EUMOFA (2018b) reported a declining production from 850 MT in 2007 down to 280 MT in 2015. This might be explained by the small size of the three main turbot producing companies involved and their poor financial performance (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022). In contrast, Portuguese production increased from 380 MT in 2000 to 3,538 MT in 2021 (FAO, 2023b), which can be explained by the improvements in efficiency of production methods and the recovery of production volumes from some farming plants (STECF, 2023). The marine aquaculture sector, which includes species such as turbot and sole, is considered the second most important segment in Portugal, representing approx. 25% of sales volume and 24% of the total sales value in 2020 (STECF, 2023).

The majority of turbot production takes place in the Iberian Peninsula (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022), most commonly grown in on-shore tanks or flat-bottomed cages (EUMOFA, 2018b). In Portugal, in addition to tanks, also Recirculating Aquaculture System (RAS) are used (STECF, 2023). RAS is also applied to produce the total output of a 100 MT in 2021, by a single supplier in the Netherlands, which also operates a turbot hatchery (EUMOFA, 2018b; FAO, 2023b). Turbot fingerling production is also observed in Denmark for the purpose of restocking and export to Spain and the Netherlands (STECF, 2021).

Turbot consumption in Spain mostly relies on farmed specimens sold through retailers and fishmongers and consumed at home. France and the Netherlands, in contrast, rely mostly on wild catch consumed outside the home (EUMOFA, 2018b), while most of the farmed production in the Netherlands (100 MT) is supplying the domestic food service industry and a small share is exported (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022; EUMOFA, 2020a; EUMOFA, 2018b). Retailers favour farmed turbot over wild-caught, because its more affordable and has a relatively stable price. Additionally, size and quality is more stable for farmed turbot, while taste differences between farmed and wild turbot are not significant (EUMOFA, 2018b).

2.2.3.3 Primary and secondary processing

The European fish (aquaculture and fisheries) processing industry fulfils an important economic role with 3,500 active firms, providing 130,000 jobs, with a total turnover of €32.5 billion in 2017 (EU28) (STECF, 2019). In terms of the number of enterprises, Spain (606), followed up by Italy (433) and the UK (341) dominate the European sector, while the largest turnovers (million €) are found in Spain (6,050), United Kingdom (3,935), Poland (2,760), Denmark (2,610), Germany (2,173) and Italy (2,109). Across Europe 98% of the processing sector is considered small and medium-sized enterprise (SME), from which approx. half are micro-enterprises. A relatively higher share of larger enterprises (above 50 employees) can be found in Eastern European countries, such as Poland and Lithuania (STECF, 2019). This might be explained by the need for scale to process imported fish from foreign fishing fleets, but also farmed Atlantic salmon from Norway. More specifically, according to STECF (2019), in the case of Poland, 163 companies were active in 2018, producing an estimated 556 thousand tonnes. The sector developed rapidly because of several innovations, including processing technology as well as product innovation towards highly processed products. An estimated 72% of the value of production was produced by companies with more than 250 employees. Labour costs are relatively low, therefore creating incentives for Danish, German and French companies to locate their fish processing companies in Poland (STECF, 2019). In the case of Lithuania in 2018, 41 enterprises were active and companies employing more than 250 people were responsible for 79% of the national turnover. Just as in the case of Poland, the Lithuanian processing industry is highly dependent on imported raw material (95%), which accounted for approx. 86 thousand tonnes in 2018. Atlantic salmon contributed to approx. 62% of total production by value and approx. 36% of total production by weight (STECF, 2019).

The Norwegian industry is relatively efficient when it comes to by-product utilisation. It manages over 650,000 MT of seafood (fisheries and aquaculture) by-products annually (Olafsen *et al.*, 2014). Nearly all the domestically produced Atlantic salmon by-products (excl. blood) originating mainly from primary processing are utilised in human food or animal feed (Richardsen *et al.*, 2017). However, there is still potential to increase volumes and value addition (Olafsen *et al.*, 2014). Additionally, a large proportion of secondary processing is outsourced to Eastern European countries, incentivised by low labour costs (STECF, 2019). As Aas *et al.* (2022a) highlighted, there is no data available on the utilisation of cut-offs of whole salmon exported to other countries. This data is crucial in order to determine the resource efficiency of the industry, in particular in relation to the retention of valuable EPA+DHA in the fillet (32%) compared to the whole fish (49%) (Aas, Åsgård and Ytrestøyl, 2022a). The utilisation of secondary processing by-products in Eastern Europe could provide direct and indirect economic benefits in terms of employment (STECF, 2019), while the by-products and their valuable nutrients can be utilised in food and feed. Alternatively, by-products that are unattractive for food products might be better directed into feed or industrial applications, such as cosmetics (Alves *et al.*, 2017), pharmaceuticals (e.g., bandages) (Rothwell *et* *al.*, 2005; Afifah *et al.*, 2019; Sharp *et al.*, 2012; Li *et al.*, 2021) and packaging (de la Caba *et al.*, 2019). Fish skin offers opportunities for the extraction of collagen and gelatine, as a more religiously acceptable source than bovine or porcine (Nurilmala *et al.*, 2017) and applications in the fashion industry in the form of fish skin leather (Palomino, 2020). Conclusively, the strategic utilisation of fish by-products could support food security, while unlocking additional economic opportunities (Stevens *et al.*, 2018).

The processing degree and the strategic utilisation potential depends partly on the consumer preferences for product form, which can vary in Europe and by species. Generally, consumers in the North of Europe prefer filleted fish, while whole (gutted) fish is more common in the South of Europe, according to a seafood consumer survey among approx. 28,000 citizens from different social and demographic categories in 28 EU member states (EC, 2018a). The preference for filleted fish creates not just additional processing opportunities, but also available by-products. However, the strategic utilisation options are limited if consumer prefer whole (gutted) fish, as most by-products accumulate on a household level. This is in particular relevant for seabream and seabass production and consumption, which is mainly taking place in Mediterranean countries (Llorente *et al.*, 2020). Gilthead seabream is considered a common commodity, but should be made more available as a value-added product (FAO, 2023f). European seabass also lacks significant processing and value addition, as it is mainly marketed fresh or whole (FAO, 2023a). Turbot is sold fresh and whole, sometimes gutted (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022; SABI, 2021). Most of the common carp in Poland is sold live during the Christmas period (Raftowicz and Le Gallic, 2019). However, in the case of rainbow trout, products vary from whole gutted fish, fillets or value-added, such as smoked trout (FAO, 2022b). Regarding the latter, a significant proportion of rainbow trout is smoked in the EU (EUMOFA, 2019b). The variety of product form might be explained by a combination of 26 rainbow trout producing countries within Europe in 2021 (FAO, 2023b), and the variety of preferences for different product forms across Europe (EC, 2018a). Unlocking additional processing and utilisation potential also requires a change in consumer preferences. European aquaculture could adopt strategies from well-established aquaculture industries, such as the Atlantic salmon industry in Norway and the Pangasius industry in Vietnam (Newton, Telfer and Little, 2014; Stevens *et al.*, 2018). Mechanical separation showed benefits to diversifying products and accessing new markets, while this process does not affect the nutritional value (Secci *et al.*, 2016). Additionally, it could benefit from knowledge and processes from other food producing industries, which partly supported the rapid growth of Atlantic salmon aquaculture. The Norwegian Atlantic salmon industry follows a relatively similar development path as poultry, but it is still only semi-automated according to Asche (2018). This indicates opportunities for further improvements and growth for the European aquaculture industry, especially the less developed value chains.

2.3 Sustainable transformation

2.3.1 Trade balance

Trade increases the resilience of the global food systems against global and regional shocks, such as increased droughts because of climate change. Trade will function as a redistributor of the resources, which increases the amount of people that can be supported by the food trade network (Dolfing, Leuven and Dermody, 2019; Gephart *et al.*, 2016). However, it also exposes countries to external perturbations (Gephart *et al.*, 2016), possibly favouring a combination of global and regional production and trade. Decreasing the dependency of the European seafood market on imports and capture fisheries would therefore increase the resilience of the European seafood market. Shorter supply chains, where production and processing are aligned, enables the aquaculture industry to use the whole fish and strategically manage and re-use by-products on a European scale. This would maximise the food, feed and industrial output (volume and value) of the aquaculture industry (Stevens *et al.*, 2018), while using resources more efficiently. This benefits the sustainability of downstream processing, as well as feed provisioning by providing ingredients with low environmental impact. This is crucial, because feed is the most significant source of environmental impact of fed aquaculture production (Bohnes *et al.*, 2018), while fulfilling a crucial role in the in the sustainable intensification process (Little *et al.*, 2018). Additionally, European aquaculture is highly dependent on imported feed ingredients (Newton and Little, 2018), exposing the sector to external shocks, which also affects its resilience (Troell *et al.*, 2014). Conclusively, circular economy principles indicate growth opportunities for European aquaculture, while enhancing sustainability, fish welfare and compliance with EU regulations on food safety and the environment. Growth through increased processing and utilisation was also achieved by the large-scale chicken industry, and the Atlantic salmon industry follows a similar development pathway (Asche, Cojocaru and Roth, 2018). According to Waite *et al.* (2014) improving aquaculture's productivity and environmental performance by means of sustainable intensification (producing more with less) makes aquaculture more competitive, while it is a crucial component of a sustainable food system.

2.3.2 Consumer preferences and domestic production

European consumers have specifically mentioned that after the date of production or catch, environmental information should be provided on all labels, according to a survey by the European commission on EU consumer habits regarding fishery and aquaculture products (EC, 2018a). Supply chains exporting to the EU are increasingly driven by external factors, such as regulatory and market pressure, as a result of increased consumer awareness towards the environment and social issues (Saeed and Kersten, 2019). Nevertheless, this does not always guarantee favourable social and environmental outcomes. According to Mialhe *et al.* (2018) based on a case study in the Philippines, global standards for aquaculture regarding food safety, traceability, socio- and environmental issues are generally designed in a top-down way not considering local specifications and complexity of aquaculture production system, leading to the exclusion of local actors while favouring larger stakeholders. This was also observed by Belton *et al.* (2017; 2016; 2016) in the case for Bangladesh because of the “pangasius boom” and shrimp exports. While overseas production creates economic opportunities for developing countries, it also resulted in divergent patterns of social change, which are unintended social outcomes developing in different directions. An example is the development of traditional Asian aquaculture which delivered wider inclusive growth in the region, while on the other hand the industrialization of aquaculture driven by export demands results in less jobs and centralized accumulation of capital (Belton and Little, 2011). The incapacity by certifiers to address these concerns and sustainability issues along complex “foreign” supply chains, in combination with increasing consumer awareness on sustainability could favour local and regional aquaculture production and consumption. Some consumers are willing to pay a premium for labelled, more sustainable products (Hynes, Ravagnan and Gjerstad, 2019; Lim, Hu and Jr., 2018; Bronnmann and Hoffmann, 2018), but this could differ depending on the product’s geographical origin (Lim, Hu and Jr., 2018) and type of product (wild-caught vs. farmed) (Bronnmann and Hoffmann, 2018). There is a perception among certain consumers that farmed fish is less healthy and has lower quality compared to wild caught fish (Claret *et al.*, 2014; Verbeke *et al.*, 2007). This might have been caused by a lack of available balanced information on production practices (Claret *et al.*, 2014; Vanhonacker *et al.*, 2011; Altintzoglou *et al.*, 2010). Additionally, some consumers prefer seafood products from local retailers because of the perception that they are of higher quality (Bronnmann and Hoffmann, 2018). For example, in Germany, the highest importance was placed on “country of origin”, while sustainability claims and labels were considered positive but less important (Risius, Hamm and Janssen, 2019). Another study showed a preference for locally produced food over “organic food”, but this could vary depending on the consumers’ place of residence and product type (Hempel and Hamm, 2016). This could be explained by the fact that the market for sustainable aquaculture products is growing but covers a relatively small market and is often less in demand by the mainstream consumer (Risius, Hamm and Janssen, 2019). Nevertheless, overall fish consumption in Europe is mostly influenced by price incentives (EC, 2018a) and a study by Zander and Feucht (2017) showed that only a fraction of the consumers in Europe is willing to pay a significant higher price for sustainably produced fish. Nevertheless, there is a growing interest in sustainable aquaculture products, reflected by the increase in certification. While there is still an overall dominance of wild catch certification over aquaculture certification (Pramod *et al.*, 2014; Potts *et al.*, 2016), certified aquaculture production has grown twice as fast compared to certified wild catch (Potts *et al.*, 2016). Changing consumer preferences could boost domestic organic aquaculture markets, which covers approx. 8% of the total European (EU-27) aquaculture production (2020), and this market segment is expected to grow, according to Euromonitor and Eurostat data (EUMOFA, 2022). This includes, but not limited to, organically certified mussels (41,936 MT), oysters (3,228 MT), Atlantic salmon

(12,870 MT), trout (4,590 MT), carp (4,590 MT) and European seabass and gilthead seabream combined (2,750 MT) in 2020 (EUMOFA, 2022).

2.3.3 Export opportunities

Asia (incl. China) produced more than 90% of the total global aquaculture production in 2020 (FAO, 2022c). China alone was responsible for 58% of the global aquaculture production in 2020, from which seaweed and carp make up 30% and 26% of their domestic aquaculture production, respectively (EUMOFA, 2022). However, China has implemented urbanisation and environmental protection legislation affecting local farmers, which will likely reduce the overall aquaculture production (Newton *et al.*, 2021a). From 2019 to 2020, a significant drop in aquaculture production in China was observed, while other Asian countries saw an increase in aquaculture production, except for Indonesia (EUMOFA, 2022). Despite the decline in production and possible causes (e.g., covid restrictions), China was considered the largest seafood market in terms of volume and value trade with third countries in 2021, followed by the EU (EUMOFA, 2022). Traditionally aquaculture trade was driven by Northern “lead” firms, but has developed into multi-polar domestic and international trade (Pieterse, 2017). A decline in Chinese aquaculture production possibly affects global seafood supply. EEA aquaculture production volumes and species diversity are insufficient to fill the supply gap. This is mainly because traditionally consumed seafood, such as carps is still very high in China (Fabinyi *et al.*, 2016). More specifically, according to a consumer survey by Fabinyi *et al.* (2016), even among middle-class urban consumers in Beijing and Shanghai, traditional freshwater products are still commonly purchased live and consumed at home. Nevertheless, an increasingly large proportion of China’s seafood is imported (Fabinyi *et al.*, 2016), while urbanisation and rising income levels drive demand for high-value species in emerging markets, such as Atlantic salmon (FAO, 2018). According to Asche *et al.* (2022), Atlantic salmon is not produced in China and therefore imported for domestic consumption, rather than for processing and re-export purposes (Asche *et al.*, 2022). It is an accepted high-value aquaculture species, also reflected by the large volumes of exported by-products (10% of Norwegian Atlantic salmon heads and frames) used in e.g., Asian soups (Stevens *et al.*, 2018).

It is important when exporting to other countries to take consumer preferences into account. Chinese consumers still prefer fresh seafood, which is often purchased “live”, compared to other product forms, such as frozen or canned seafood (Zhong, Crang and Zeng, 2019). It is estimated that a large proportion (~60–80%) of seafood in China is still purchased in live form in wet markets, without packaging, and is not easy to label or trace, thus certifications are not easy to promote with these products. In contrast, most seafood in developed countries is imported in processed forms, which are often labelled and traceable (Guan *et al.*, 2021; Peng *et al.*, 2020; Sun *et al.*, 2021). The packaged export of e.g., processed Atlantic salmon (by-products) to China indicates opportunities to message cultural values that are important to the Chinese consumer, which might increase sales. More specifically, as Fabinyi (2016) highlighted, Chinese governance, traders, and consumers have a greater emphasis on food safety, traceability, quality, and freshness, rather than environmental sustainability.

2.4 Value chain innovation to support sustainable intensification

2.4.1 Measuring sustainability with a focus on environmental impact

Sustainable development is defined by the famous Brundtland report; *Our Common Future* (UN, 1987) as “meeting the (nutritious) needs of the present generation, without compromising the ability for future generations to fulfil their own needs”. Therefore a holistic “food system approach” is crucial to avoid problem shifting (Cook *et al.*, 2015). As Poore & Nemecek (2018) pointed out, impact reduction is associated with trade-offs, with results in gaining in one area, while diminishing in another. While impacts at the farm (energy use, nutrient and chemical release) are relevant, the majority of the environmental impact of fed aquaculture production is embodied in feed (Bohnes *et al.*, 2018). More specifically, Newton and Little (2018) showed for Scottish Atlantic salmon farming that the majority of the environmental impacts were embodied within imported marine and terrestrial feed ingredients. This was measured using Life Cycle Assessment (LCA), which is an environmental impact assessments capable of identifying hot spots in the production process (Curran, 1993; Guinée, 2002; ISO, 1997; ISO, 2006), including the incoming (food production, energy, water and other resources used) and out-coming (main product, by-products and emissions) flow (Samuel-Fitwi *et al.*, 2012). As pointed out by Newton and Little (2018), it is important to contextualize the value chain in order to understand the effects of local production on a global scale.

Combining a value chain approach with LCA is a crucial process to understand the “bigger picture”. However, LCA mainly includes environmental sustainability indicators, and this should be expanded. Such an evaluation goes beyond “environmental” sustainability, and could include socio-economic quantitative and qualitative indicators (Valenti *et al.*, 2018). This includes, but is not limited to, poverty implications and welfare (Bolwig *et al.*, 2010)**,** gender equality (Kruijssen, McDougall and van Asseldonk, 2018), economic inclusivity of large vs small scale aquaculture (Belton and Little, 2011), distribution of economic benefits in the value chain (Kassam and Dorward, 2017), trade-offs between labour and resource use (Gonzalez-Poblete *et al.*, 2018), and economic firm and social upgrading (Barrientos, Gereffi and Rossi, 2011), as well as fish welfare indicators (Barreto *et al.*, 2021).

2.4.2 System change

Sustainable transformation requires a system change. In regards to the energy system, three mechanisms were seen as a barrier for the sustainable transformation and characterised by Unruh's (2000) "carbon lock-in", as highlighted in the study of Geels *et al.* (2008). These barriers could be similar to the challenges the sustainable transformation of the food system is facing. First, sustainable technologies might be more expensive. While they have a collective good (clean environment), costs are paid by individual users hindering the innovation process (Jacobsson and Bergek, 2004). Second, uncertainties about future markets and regulations function as a barrier to develop sustainable technologies (Geels, Hekkert and Jacobsson, 2008). Third, existing sociotechnical systems and technologies are in an advantageous position and stabilised, because of so called "lock-in mechanisms", such as scale economies, sunk investment and consumer behavioural patterns (Unruh, 2000; Walker, 2000; Freeman and Perez., 1988).

According to Geels *et al.* (2008), three strategies show useful elements, but are insufficient to deliver a significant system change. More specifically:

1. *Neo-liberal strategies*, environmental issues lead to higher prices, which will change consumer behaviour towards more sustainable products (Geels, Hekkert and Jacobsson, 2008)
2. E*cological modernisation*, a technological fix with modernist principles such as technical progress, science, control and economic growth (Mol, 2001)
3. *Deep ecology*, suggest a behavioural change towards green values, also called an eco-centrist approach (Næss, 1973; Katz, Light and Rothenberg, 2000; Walker and Devine-Wright, 2008; Curry, 2011). According to Geels *et al.* (2008), insufficiency of these approaches is due to the generalization of sustainability as a whole and the lack of a system approach.

Therefore, a fourth strategy is emphasised by Geels *et al.* (2008), called "socio-technical transitions" seeing sustainability issues as a system or sectoral challenge, covering the use of new technologies, societal changes, changes in user practices, markets, policy, and governing institutions (Rohracher, 2001; Jacobsson and Bergek, 2004; Smith, Stirling and Berkhout, 2005; Geels and Raven, 2006; Geels, 2006; Geels, 2005; Hekkert *et al.*, 2007). This approach is focussing on the totality of relevant actors, beyond firms, consumers, and markets (DiMaggio and Powell., 1983). It covers a shift to new forms of energy, transport, housing, and agrifood systems, which involves socio-technical transitions beyond technology, including consumer practices, policies, cultural meanings, infrastructure, and business models (Geels, 2018; Geels, 2019). This is in line with the literature study of Joffre *et al.* (2017) concluding that aquaculture innovation would benefit from systematic approaches and taking the important role of private sector actors in consideration, while emphasizing the important role of interdisciplinary research enhancing resilience and sustainability of the sector. This is important when dealing with complex aquaculture systems and multiple involved actors (Joffre *et al.*, 2017).

While this study identified three main bodies of literature on approaches to conceptualize and manage innovation, such as "technology-driven", "systemic", and "business and managerial", currently the dominant approach to aquaculture innovation is "transfer of technology", with most of the identified literature focussing on the farm level and technology (Joffre *et al.*, 2017). However, this theory is challenged by the Actor Network Theory (ANT), which acknowledges that the social and natural world are a constant shift of networks and relationships on a technical, organizational, and institutional level. Economy and society can't be defined as a simple context or structure (Callon, Latour and Law, 2019). This composition and structure affect the way change is adopted and this theory provides understanding of the processes of innovation and transition. It is important to take a larger perspective on innovation, as Afewerki *et al.* (2022) pointed out that most innovations (from 1970 until present) were conducted by suppliers and not by the aquaculture producers themselves. Most of these innovations range from radical new concepts to knowledge adoption from the terrestrial food production system (Afewerki *et al.*, 2022). This shows overlap with the study of Asche *et al.* (2018) on Norwegian Atlantic salmon, highlighting that innovations and development pathways can be adopted from other industries, such as the poultry industry (Asche, Cojocaru and Roth, 2018). The Atlantic salmon industry in Norway has grown through (directly) economics of scale by development of farm and company size, and (indirectly) R&D, innovation, sales, and marketing. Some of these practices could also be transferred to other finfish species, such as seen with cages used for European seabass and gilthead seabream. This could be expanded for feed approaches and the strategic utilisation of aquaculture processing by-products.

2.4.3 Policy

More specifically to aquaculture, the EU "Farm to Fork Strategy" is focussing on the sustainable transformation of the food sector, enhancing sustainable production and consumption, food security, reducing Europe's dependency on imported proteins (e.g., livestock feed), reducing food loss and waste, while combating food fraud along the supply chain, involving all operators in the food value chain (EC, 2008; EC, 2020b). However, in terms of the strategic utilisation of fish by-products, policies such as 1069/2009 (EC, 2009) should be reviewed, as it currently prohibits the feeding of farmed fish with processed animal protein derived (partially) from farmed fish of the same species. The ban on intra-species feeding has major implications for e.g., Norway, as it has dominant production of the same species, namely Atlantic salmon, and rainbow trout. Intraspecies feeding could result in an infectivity pool, leading to an epidemic or health risk to the consumer (EC, 1999). Nevertheless, these concerns can be traced back to the lack of transparency and traceability of the industry.

2.5 Discussion

A significant proportion of global seafood is traded, which affects domestic markets and exposing local fishers as well as fish farmers to competition from imports (Asche, 2015; FAO, 2010). The EU is the largest importer and exporter of agri-food products and largest seafood market in the world (EC, 2020a). Three quarters of the EU seafood supply finds it origin from (import) capture fisheries (EUMOFA, 2022). Consequently, European aquaculture is lacking scale, and growth capacity is undermined by cheaper alternatives from capture fisheries and (aquaculture) imports. The EU "Farm to Fork Strategy" is designed to support the transition to a sustainable food system (EC, 2020a). It is important to avoid the externalisation of unsustainable practices (e.g., through imports) and enhance the economic performance of primary producers, while reinforcing EU's competitiveness (EC, 2020a). This is particularly important for aquaculture and its high levels of interaction (e.g., nutrient flows) with fisheries and agriculture (Blanchard *et al.*, 2017; Pounds *et al.*, 2022).

Feed provisioning is a crucial component in the sustainable intensification process (Little *et al.*, 2018). However, it is responsible for the majority of environmental impact and costs of fed aquaculture production (Bohnes *et al.*, 2018; Rana, Siriwardena and Hasan, 2009) and European aquaculture is highly dependent on imported feed ingredients from the marine and terrestrial system (Newton and Little, 2018). To make aquaculture more sustainable, competitive, and resilient, it is crucial to improve the resource efficiency of the industry. Therefore it is important to first explore the use of readily available resources in the form of fish by-products, which could be more efficiently processed and utilised for human consumption and animal feeds (Stevens *et al.*, 2018). This would increase the production in terms of volume and value output, without the need for additional resources (Stevens *et al.*, 2018), a perfect example of sustainable intensification. While this strategy benefits the sustainability of downstream processing, it could indirectly improve the sustainability of animal feed provisioning in Europe as well. More specifically, it could reduce the need for whole fish for FM and FO production, and their substitutes, such as plant derived meals and concentrates (Newton and Little, 2018; Blanchard *et al.*, 2017; Malcorps *et al.*, 2019a). Additionally, it could benefit the livestock industry, as the EU is the largest user of proteins produced from vegetable origins, and reducing the dependency on feed protein imports was also considered an important strategy towards a sustainable transformation of the EU food system (FEFAC, 2023). For example, locally produced protein, in the form of faba beans shows potential to replace soy in pig feed (EUPiG, 2020).

Understanding the real impact of the sustainable intensification strategies requires exploration of the optimal use in the value chain, maximising economic and environmental gains while enhancing the competitiveness and resilience of European aquaculture. More specifically, this would require a by-product and value chain analysis of the most important stakeholders in the European value chain, envisioned around geographical processing and utilisation clusters. An example is the Iceland Ocean

Cluster promoting a 100% utilisation of the whole fish (IOC, 2023). In these clusters knowledge and technology can be exchanged and utilised to advance the resource efficiency performance and growth of European aquaculture species. Additionally, optimising productivity is a key concept of sustainable intensification for agricultural systems, so that arable land does not have to be expanded with potential biodiversity and ecosystem loss (Cook *et al.*, 2015). It is crucial to find the right basket of feed ingredients, which are available, affordable, have a low environmental footprint and most importantly, meet the nutritional requirements of the farmed fish.

2.6 Conclusion

European aquaculture is lacking scale and growth capacity is undermined by cheaper alternatives from capture fisheries and (aquaculture) imports (STECF, 2021). Increasing the resource efficiency upstream (feed) and downstream (processing) value chain could benefit the economic and environmental performance. More specifically, the potential of (novel) feed ingredients in terms of nutritional and environmental performance should be explored, while addressing availability, scale, and price issues (Pelletier *et al.*, 2018; Hua *et al.*, 2019). Downstream value chain, the strategic utilisation of fish by-products in food, feed and industrial applications could increase the volume and value output, without the need for additional resources (Stevens *et al.*, 2018). This could also reduce the need for marine ingredients for whole fish and their FM and FO substitutes, with associated negative impact on the environment and on the nutritional value of the final aquaculture product (Nichols *et al.*, 2014; Sprague, Dick and Tocher, 2016; Newton and Little, 2018; Saito *et al.*, 2020). Nevertheless, consumer perceptions causing a geographical discrepancy in available by-products, and in addition infrastructure and legislation act as a barrier for the strategic utilisation of aquaculture processing by-products in food, feed, and industrial applications.

Aquaculture interacts with fisheries and agriculture, mainly through nutrient lows (Blanchard *et al.*, 2017; Pounds *et al.*, 2022). Therefore, a “food system approach” is crucial in order to understand the sustainability (socio-economic and environmental) trade-offs as a result of the implementation of new innovations, such as increased fish processing or the use of other aquafeed ingredients (Cook *et al.*, 2015). Such an approach avoids problem shifting (Cook *et al.*, 2015), which is crucial to support the sustainable intensification of European aquaculture, while enhancing the resilience of global food systems and providing a steady supply of affordable, healthy, and nutritious seafood to consumers.

CHAPTER 3: STAKEHOLDER PERCEPTIONS

3.1 Introduction

To better understand European aquaculture and the opportunities and challenges regarding sustainable intensification, a stakeholder perception survey was conducted for both Norwegian Atlantic salmon and Polish common carp industries. Key points of comparison were the industrial scale of Norwegian Atlantic salmon aquaculture with an export focus (Torrissen *et al.*, 2011), compared to the extensive and traditional characteristics of the Polish common carp industry, mainly for domestic consumption (Raftowicz and Le Gallic, 2019).

The stakeholders can be defined as participants in any action or process, providing resources, production capability, skills, innovation, and governance to an industry and consumers. In the case of Norwegian Atlantic salmon and Polish common carp industry, a stakeholder perception survey is required to understand the position and characteristics of any important participant within these industrial and traditional value chains, respectively. A stakeholder perception survey can help to understand the challenges faced by the industry and the successes, which might be transferable between industries. The survey presented here focused on stakeholder perceptions and attitudes to other actors. This includes their perceptions towards sustainability, innovation, and sustainable intensification measures. This information is crucial, as these perceptions and attitudes could have significant impact on the continued sustainability of the industry and the potential to implement innovation; technologically, structurally or politically (Joffre *et al.*, 2017; Karim *et al.*, 2020; Lebel *et al.*, 2021; Obiero *et al.*, 2019).

Stakeholders were asked about “sustainable growth” due to its familiarity, but we refer in text to “sustainable intensification”, summarized as the aim to increase (crop) yields and economic returns without negative impacts on the environment (Godfray and Garnett, 2014; Cassman and Grassini, 2020).

3.2 Methodology

A mixed methods approach (Figure 3.1) was used to analyse the Atlantic salmon (Norway) and common carp (Poland) aquaculture industry.

1. Visualizations of the stakeholder actors involved were created based on the available literature (CH1-2) and discussions with the Green Aquaculture Intensification (GAIN) in Europe project group. This was supported by *Agri benchmark* – a non-profit network of producers, advisors, economists and specialists in key sectors of global agricultural and horticultural value chains analysing farms, production systems and their profitability (Agribenchmark, 2019).
2. Interviews with key informant(s) (KI) focussing on obtaining quantitative and qualitative data from both industries, including perceptions towards sustainability, challenges, and opportunities.
3. Delphi survey to gain understanding in the consensus and diversity of opinions in both industries building on the KI results (2).

The duration of the workshop was three days and involved different GAIN project partners involved in the most important European aquaculture value chains, such as the Norwegian Atlantic salmon and Polish common carp, but also rainbow trout, gilthead seabream, European seabass and turbot (Agribenchmark, 2019). Attendees were put into groups and asked to describe the value chain and construct basic flow charts, including the main actors and stakeholders involved (Table 3.1). This work was also the foundation of two other report outputs, such as the "*Report on value chain analysis* (Malcorps *et al.*, 2021b)", as well as the "*Report on value chain mapping for key species/systems, with SWOT analysis of key informants* (Malcorps *et al.*, 2019b)."

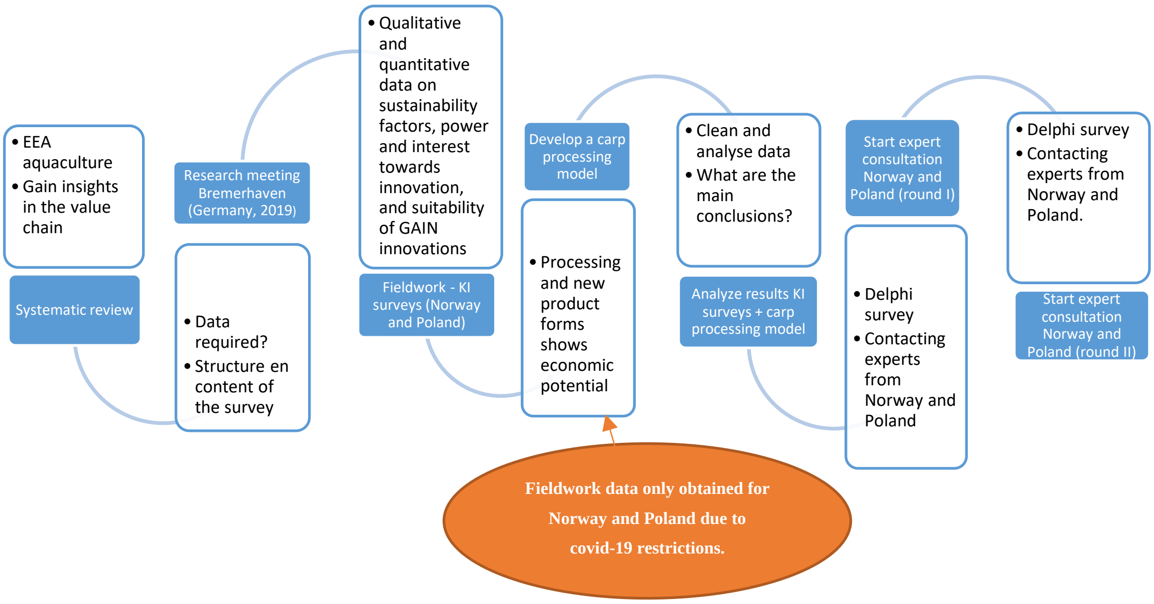


Figure 3.1: Mixed method approach to analyse the value chain of Norwegian Atlantic salmon and Polish common carp (Poland).

The survey was piloted in Norway (July – September 2019), when value chain stakeholders (Table 3.1) were interviewed face to face, although some surveys were conducted by video calls and emails into 2020. Fieldwork in Poland was conducted February - April 2020. However, this was cut short in response to the COVID-19 pandemic restrictions in March 2020. Surveys were continued by video calls and emails with the help of Polish project partners. The key informant interviews included quantitative and qualitative data, starting with details on the company/business and interviewee and some basic open questions about the value chain.

Sample frame

This was followed up by more detailed questions on the power and interest of other stakeholder (actors) to make industry changes and innovate. Furthermore, survey questions on knowledge, attitudes and perceptions regarding aquaculture intensification, sustainability, novel feeds, and circular economy innovations. More details regarding the questions in the KI survey can be found in the supplementary materials (Appendix A1.1 and A1.2).

Table 3.1: The identified value chain stakeholders and aggregated categories for Norwegian Atlantic salmon and Polish common carp. Not all stakeholders are applicable to both countries.

Stakeholder	**Aggregated category**
Brood stock/egg producers	Producers
Hatcheries (RAS)	
Smolt production (RAS)*	
Smolt production (flow-through)*	
(Grow-out) farms	
(Independent) slaughterhouse and primary processors	
Independent secondary processors	
Value addition processors/smokeries etc.	
Integrated companies	
By-product processors	Others
Cleaner fish producers	Supporting
(Exporters/import) trading companies	
Retail	Others
(Well-boat)/transport*	Supporting
Vet/health management companies	
Feed companies	
Ingredient producers (FO, hydrolysates/meals etc.)	Others
End users	
Education (university) groups	Research
Research innovation (R&D) companies/institutes	
Recreational (guide) tour	Others
Trainer institution (learning centre)	
Equipment producers	Supporting
Government authorities	Others
Certifiers	
NGOs	
Consumer groups/associations	
Carp association	
Other support industries/suppliers (ice, chemicals, consumable products etc.)	

**Well-boat and smolt facilities only applicable to the Norwegian Atlantic salmon aquaculture industry.*

After the finalization of the KI interviews, the data was cleaned in consultation with a senior colleague to avoid bias and analysed using excel spreadsheets. More specifically, important findings were selected and explored in depth with the help of two rounds of a Delphi expert consultation, targeting opinion and consensus around certain practices and perceptions. The Delphi survey was distributed electronically by email. The first round of questions for the Norwegian Atlantic salmon value chain experts were related to aquaculture trends, sustainability and public perceptions towards aquaculture, legislation (European, national, and regional level), sustainable intensification and profitability strategies, technology to combat sea lice, novel feed ingredients and their potential to improve feed efficiency, environmental sustainability, fish welfare and consumer perception. The first round of questions for the Polish common carp value chain experts were relatively similar, except for questions in relation to sea lice or novel feed ingredients, as this is not relevant. Instead, the first round focused on carp processing, marketing, and climate change. More details can be found in Appendix A1.3 and A1.4. The second Delphi round was built on the responses of the first round. More details can be found in Appendix A1.5 and A1.6

3.2.1 Power and interest to make industry changes

A power interest matrix was developed, based on consolidated stakeholder analysis techniques (Eden and Ackermann, 2011). A power interest matrix is a tool that maps the power and influence of stakeholders within an industry. It is useful because it helps policy makers to identify stakeholders for driving innovation and sustainability in the industry. It is a useful tool to understand the opportunities and barriers for innovation and the characteristics of the industry towards innovation. The "power" of stakeholders is defined as those actors who can influence change within the value chain, whereas the "interest" of stakeholders are those actors who are most affected by any change to the value chain. A strong positive relationship between power and interest indicates that value chain development is stakeholder driven. If there is little relationship between power and interest or power rises slowly with interest, then the value chain may not be stakeholder driven and change may not be meeting the needs of stakeholders most affected.

To reduce bias, stakeholders were not asked to score themselves or other stakeholders of the same type, but to score the power and interest of other types of stakeholders along the value chain from 1 (barely any influence) to 10 (highly influential). The average power and interest scores were calculated and plotted per stakeholder group to identify stakeholders with high interest and/or high power and establish any relationship between the power/interest dynamic.

Relationships between stakeholder opinions and the power/interest dynamic were tested statistically.

1. A general linear model (GLM) was applied to test the relationship between power and interest followed by a Tukey Pairwise comparison (95% confidence) to test if there was a significant difference in terms of "power" or "interest" between stakeholder categories.
2. A regression analysis was applied to define the relationship between power versus interest of the stakeholders overall.

3.2.2 Sustainability perceptions

Participants were asked to identify sustainability factors in their sector, separating out issues which may have a positive or negative effect on the sustainability of the industry going forward and those which they were uncertain about (Table 3.1). Each mention of a specific positive, uncertain, or negative sustainability factor received one point. The sustainability factors in each category (positive, uncertain, or negative) were selected by the stakeholder and ranked according to the number of points scored.

3.2.3 Awareness of the different innovations

The GAIN project consortium identified a variety of innovations in development to support the sustainable growth of the aquaculture industry (Table 3.2). This was based on many decades of experience by a variety of companies, organisations and individuals from industry and academia, as part of the project consortium.

Table 3.2: List of innovations and description.

Innovations	**Description**
Microalgae	Phytoplankton found in freshwater and marine systems as a feed ingredient
Macroalgae	Seaweed as feed ingredient
Hydrolysed fish proteins	Concentrations of free amino acids and low molecular peptides as feed ingredient
Single cell proteins	Such as yeast, fungi, bacteria, and algae as feed ingredient
Insect protein	Feed ingredient derived from insects
Sludge for fertiliser	Semi-solid slurry from a fishpond or RAS used as organic fertiliser
Sludge for biogas	Semi-solid slurry from a fishpond or RAS used as biogas
Mortalities for biogas	Mortalities from the hatchery, smolt facility or farm used as biogas
Processing by-products for feed	Process fish by-products (secondary product) for use as feed ingredient
By-products for cosmetics/nutraceuticals	Process fish by-products (secondary product) for cosmetics/nutraceuticals
Shells for biofilters	Shells from e.g., mussels or oysters to be used as high surface area filter substrate
Shells for packaging	Shells from e.g., mussels or oysters to be used as packaging material
Shells for cement/filler	Shells from e.g., mussels or oysters to be used as cement
Use of big data management support	Large datasets from different sources to enable better decision making on site
Use of big data for welfare	Large datasets from different sources to support better fish welfare

Interviewees from the aquaculture industry were asked about their knowledge on the selected innovations. Their perception of innovations was separated by different levels of awareness; “personal awareness/knowledge”, “company interest” and “industry interest” towards each innovation listed. Each innovation was scored according to the degree of knowledge or interest across the three levels (equal weighting). A maximum score of 6 could be achieved for each respondent based on a yes (2), uncertain (1) or no (0) score for each level of awareness per innovation. High scores were used as an indication of high potential for implementation because of the stated alignment with the collective views of stakeholders, as people showed awareness of the benefits for their company/industry. Statistics (Tukey pairwise comparisons) were applied to test if there was a significant difference between the scoring of the innovations between the aggregated stakeholder categories.

3.2.4 Delphi survey

In response to the main findings of the KI surveys in Norway and Poland, a Delphi survey was developed to add depth to the results and to gain additional insights. The Delphi survey is the concept of using a panel of experts to achieve consensus around a problem or to agree on a solution path for a particular problem (Avella, 2016). Such a concept is particularly important in an industry in development, where stakeholders tend to have different opinions depending on its position in the value chain. Asking a group of people from the respective value chains similar questions provides a more reliable insight in the current practices and possible future pathways, especially regarding the sustainable intensification of the industry. The Delphi method employed here included two survey rounds to investigate stakeholder opinion on key sustainability issues, industry trends, innovation, and legislation, and can be found in Appendix A1.3-A1.6. The question varied from multiple choice to a scoring system (1 “not important”, 8 “highly important”). Likert scale questions were also used to measure attitudes, in which the interviewee rated the degree to which they disagree or agree to a certain statement (Likert, 1932).

The first Delphi round also included questions to score the relative importance of individual sustainability indicators in the Eco-intensification Sustainability Index (EISI) within the GAIN project (Newton *et al.*, 2021b). The EISI was a collaborative effort between the University of Stirling, University of Venice, West Pomeranian University of Technology (Zachodniopomorski Uniwersytet Technologiczny w Szczecinie – ZUT), Thünen Institute, Gildeskål Forskningsstasjon (GIFAS), Agri-Food and Biosciences Institute (AFBI) and others. It was built on earlier project experiences, such as the FP7 funded SEAT and H2020 funded EURASTiP, and further developed through iterative sessions and workshops focussing on value chains and sustainability as part of the GAIN project. The aim was to develop a toolkit that is applicable to the whole aquaculture value chain and that has a wider scope than just “environmental sustainability” included in Life Cycle Assessment

(LCA). This sustainability tool is focussing on environmental, socio-economic, and animal welfare indicators, covering a wide range of issues linked to the "*One Health*" concept and is therefore capable in taking into account unexpected consequences or sustainability trade-offs along the value chain. However, certain EISI indicators might be more relevant between value chains. The development of the EISI toolkit was not the main focus of this thesis, but understanding the relevance of indicators was instrumental. Therefore, I asked the panel of experts to score (from 1-8 from least important to highly important) each indicator separately based on their own understanding of the importance of this indicator in their value chain (Appendix A1.3-A1.6). This data was used to score the relative importance of the sustainability indicators, which was included in another GAIN report "*EISI sustainability approach, results and analysis*" (Newton *et al.*, 2021b).

3.3 Results

The results of the *Agri benchmark* (2019) workshop are shown below. Figure 3.2 shows the flow chart that the salmon focus group developed.

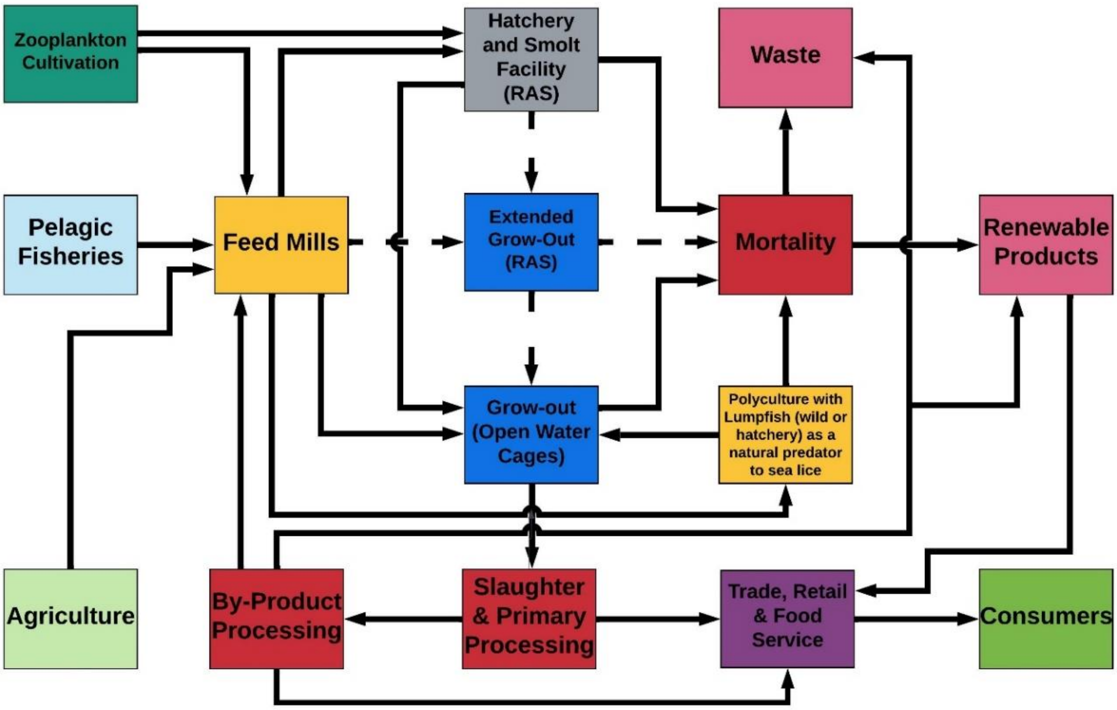


Figure 3.2: Value chain of Norwegian Atlantic salmon. The dotted and dashed lines indicate different and changing approaches, respectively (made by the author with Lucidchart based on the literature review and discussions in Bremerhaven).

The Norwegian Atlantic salmon value chain shows significant differences compared with the more extensive and traditional characteristics of the Polish common carp industry (Figure 3.3).

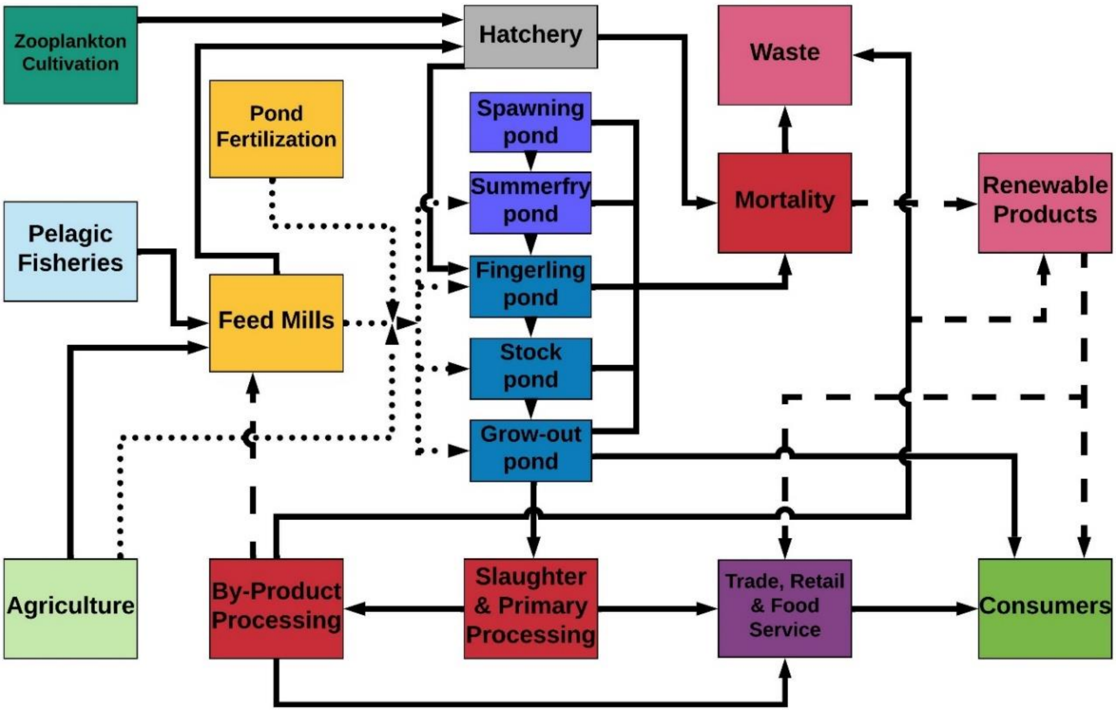


Figure 3.3: Value chain of Polish common carp. The dotted and dashed lines indicate different and changing approaches, respectively (made by the author with Lucidchart based on available literature as described in Chapter 2).

A total of 31-33 and 12-21 actors from the Norwegian Atlantic salmon and Polish common carp value chain were interviewed as part of the KI survey, respectively. Response rates varied to different part of the survey, depending on the awareness or willingness of the stakeholder to answer certain questions. Despite this there was a good overall response rate between stakeholders for both value chains (Table 3.3).

Table 3.3: Surveyed KI stakeholders in partner countries for Norwegian Atlantic salmon and Polish common carp. Not all stakeholders applicable to all countries. Sample size (N) could slight differ per section of the survey, depending on the willingness to answer.

Stakeholder	**Aggregated category**	**Norway (June-Sept 2019)**	**Poland (Feb-April 2020)**
		Atlantic salmon (N=31-36)	**Common carp (N=12-22)**
Brood stock/egg producers	Producers	x	
Hatcheries (RAS)		x	
Smolt production (RAS)*		x	
Smolt production (flow-through)*		x	
(Grow-out) farms		x	x
(Independent) slaughterhouse and primary processors		x	x
Independent secondary processors		x	
Value addition processors/smokeries etc.		x	x
Integrated companies		x	
By-product processors	Others	x	
Cleaner fish producers	Supporting	x	
(Exporters/import) trading companies		x	x
Retail	Others	x	x
(Well-boat)/transport*	Supporting	x	x
Vet/health management companies		x	x
Feed companies		x	x
Ingredient producers (FO, hydrolysates/meals etc.)	Others	x	
End users		x	
Education groups	Research	x	x
Research innovation (R&D) companies/institutes		x	x
Recreational (guide) tour	Others		x
Trainer institution (learning centre)		x	x
Equipment producers	Supporting	x	x
Government authorities	Others	x	x
Certifiers		x	x
NGOs		x	x
Consumer groups/associations		x	x
Carp association			x
Other support industries/suppliers (ice, chemicals, consumable products etc.)		x	

**Well-boat and smolt facilities only applicable to the Norwegian Atlantic salmon aquaculture industry.*

The results of the KI survey (Table 3.3) and Delphi survey (Table 3.4) are shown in the following sections.

Table 3.4: Industry responses from stakeholders in two Delphi rounds.

Value chain actors/stakeholders	**Aggregated category**	**Norwegian Atlantic salmon**		**Polish common carp**	
		Delphi Round			
		1 (n=11)	**2 (n=11)**	**1 (n=15)**	**2 (n=12)**
Brood stock/hatchery	Producers		x		
Farm		x	x	x	x
Slaughterhouse and processing			x	x	
Feed	Supporting	x	x	x	x
Vet/health			x	x	x
Trade			x		
Equipment producers		x			
Recreational	Others			x	
Education, research, and academia	Research	x	x	x	x
NGO	Others				x
Certifiers		x			
Government					x
Others			x		x

3.3.1 Stakeholder power and interest to make industry changes

This section provides the power and interest results of the stakeholders to drive innovation.

Norwegian Atlantic salmon

Table 3.5 shows the number of each type of stakeholder interviewed within the Norwegian Atlantic salmon value chain. Most stakeholders in the Norwegian industry show high power and high interest in innovation and therefore most of them are grouped in the top right corner of the grid shown in Figure 3.4. Especially important are government authorities, NGOs, certifiers, and consumer group/associations, which are considered very powerful and with a medium to high interest in innovation. Interestingly, the processing sector in Norway shows a high interest in innovation, but a relatively lower score for power to drive the necessary changes.

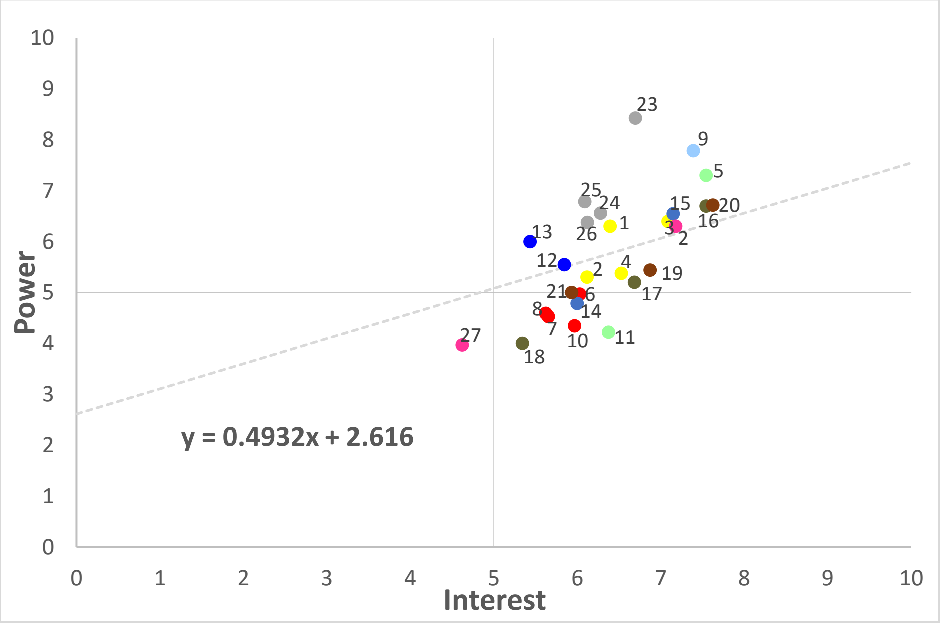


Figure 3.4: Power/interest to make industry changes in Norway. Colours (nodes) and data labels (specific stakeholders) refer to Table 3.5.

There was a significant and steep relationship between power and interest overall (P-value<0.0001, R-sq = 24.67%) as seen in Figure 3.4. This indicates that the most affected (interested) stakeholders are those with highest ability to affect change (powerful) and that the industry is broadly stakeholder led.

A comparison for interest (Tukey Pairwise Comparisons: Scored Aggregated cat.) indicated a significant difference (p=0.004) between research and all other stakeholders apart from producers in terms of interests to innovate (Table 3.5).

Table 3.5: Stakeholder actors active in the Norwegian Atlantic salmon value chain. Colours (nodes) and data labels (specific stakeholders) refer to Figure 3.4.

Nodes	**Data label**	**Stakeholder**	**n=31-33***	**Power Score**	**SD^1**	**Interest Score**	**SD^1**	**Cat.^{2}**	**Power^3**	**Interest^3**
Early life stage	1	Brood stock/egg producers	1	6.3	2.1	6.4	2.7	Producers	A	AB
	2	Hatcheries (RAS)		5.3	2.3	6.1	2.7			
	3	Smolt production (RAS)	1	6.4	2.2	7.1	2.5			
	4	Smolt production (flow-through)		5.4	2.4	6.5	2.7			
Grow-out	5	Grow-out farms	3	7.3	2.1	7.5	2.3			
Processing	6	Independent slaughterhouse and primary processors	1	5.0	2.1	6.0	2.2			
	7	Independent secondary processors	1	4.5	2.2	5.7	2.6			
	8	Value addition processors/smokeries etc.		4.6	2.3	5.6	2.6			
Integrated	9	Integrated companies		7.8	1.9	7.4	2.4			
Processing	10	By-product processors	1	4.3	2.1	6.0	2.6	Others	A	B
Grow-out	11	Cleaner fish producers		4.2	1.8	6.4	2.6	Supporting	A	B
Trade	12	Exporters/trading companies	1	5.5	2.5	5.8	2.2			
	13	Retail		6.0	2.7	5.4	2.4	Others	A	B
Health	14	Well-boat/transport	1	4.8	2.1	6.0	2.6	Supporting	A	B
	15	Vet/health management companies	3	6.5	2.0	7.2	1.7			
Feed (ingredients)	16	Feed companies	3	6.7	2.1	7.5	2.0			
	17	Ingredient producers (FO, hydrolysates/meals etc.)		5.2	2.5	6.7	2.3	Others	A	B
	18	End users	1	4.0	2.4	5.3	2.8			
Education	19	Education groups	2	5.4	2.3	6.9	2.2	Research	A	A
	20	Research innovation companies (R&D)	4	6.7	2.2	7.6	2.2			
	21	Trainer institution (learning centre)	1	5.0	2.2	5.9	2.3	Others	A	B
Equipment	22	Equipment producers	2	6.3	2.2	7.2	2.1	Supporting	A	B
Third parties	23	Government authorities	1	8.4	1.3	6.7	2.5	Others	A	B
	24	Certifiers	3	6.6	2.4	6.3	2.3			
	25	NGOs	1	6.8	2.1	6.1	2.9			
	26	Consumer groups/associations		6.4	2.6	6.1	2.2			
Equipment	27	Other support industries/suppliers (e.g., chemicals, consumable products)	2	4.0	2.3	4.6	2.3			

**Sample size (N) could differ per scored stakeholder, depending on the awareness or willingness of the stakeholders interviewed (33 total) to score the power and interest of certain stakeholders.*

^{1}*Standard deviation*

^{2}*Aggregated stakeholder category based on table 3.1*

^{3}*Grouping information using the Tukey method and 95% confidence: Scored Aggregated cat. comparison for power and interest. Aggregated categories that do not share letter(s) in terms of power or interest are significantly different.*

Polish common carp

Table 3.6 shows the number of each type of stakeholder interviewed within the Polish common carp value chain. The stakeholders in Poland show low correlation of power to interest to make industry changes. Power does not increase as sharply with interest in the Polish value chain as in the Norwegian salmon industry, indicating that this value chain is less stakeholder driven and there is a lower appetite for change (Figure 3.5). Government and representative authorities and retail companies are considered powerful, with the latter also showing relatively high interest in change/innovation. NGOs are showing the highest interest in change and innovating the common carp industry in Poland.

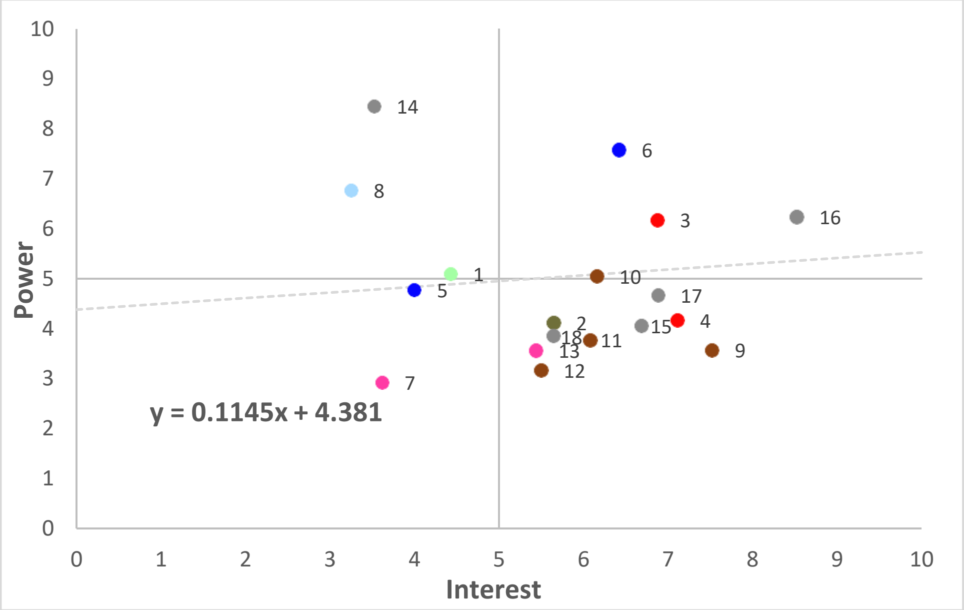


Figure 3.5: Power/interest to make industry changes in Poland. Colours (nodes) and data labels (specific stakeholders) refer to Table 3.6.

The stakeholders in Poland show low correlation of power to interest to make industry changes, although there was a significant relationship (P-value=0.034, R-sq =1.46%) (Figure 3.5). The relationship between the stakeholders is less clear than for Norway, characterised by a more scattered, less steep regression line and lower R-sq, indicating high variation and poor fit (Figure 3.5). A pairwise comparison (Tukey) for power and interest between stakeholders indicated that there is a significant difference between “others”, “supporting”, and “producers” and “research”. In terms of interest there is a significant difference between “research”, “others”, and “producers” and “supporting” (Table 3.6).

Carp processors showed a relatively high interest in innovation, but relatively low power (Figure 3.5). Interestingly, retailers and NGOs (environmental and ethical groups) showed high power and high interest to make industry changes.

Table 3.6: Stakeholder actors active in the Polish common carp value chain. Colours (nodes) and numbers (specific stakeholders) refer to Figure 3.5.

Nodes	**Data label**	**Stakeholder**	**n=12-21***	**Power Score**	**SD[1]**	**Interest Score**	**SD[1]**	**Cat.[2]**	**Power[3]**	**Interest[3]**
Grow-out	1	Farms	3	5.1	2.7	4.4	2.3	Producers	AB	AB
Feed (Ingredients)	2	Feed companies	2	4.1	2.6	5.6	3.3	Supporting	A	B
Processing	3	Slaughterhouse and primary processing	1	6.2	2.7	6.9	2.4	Producers	AB	AB
	4	Value addition processing		4.2	2.5	7.1	2.1			
Trade	5	Important and trading company		4.8	2.7	4.0	2.9	Supporting	A	B
	6	Retail company		7.6	2.0	6.4	2.4	Others	A	A
Equipment	7	Transport		2.9	1.1	3.6	2.5	Supporting	A	B
Health	8	Vet/Health management company	1	6.8	3.3	3.3	2.5			
Education	9	Education	5	3.6	2.1	7.5	2.8	Research	B	A
	10	Recreational (guide) tour	1	5.1	2.8	6.2	3.3	Others	A	A
	11	Research and innovation institute (R&D)	4	3.8	2.2	6.1	2.1	Research	B	A
	12	Trainer institution (learning centre)		3.2	1.5	5.5	3.3	Others	A	A
Equipment	13	Equipment producer, maintenance, and recycling		3.6	2.4	5.4	2.3	Supporting	A	B
Third parties	14	Government and representative authorities		8.5	2.5	3.5	2.3	Others	A	A
	15	Certification body/organization		4.1	2.6	6.7	3.3			
	16	NGOs	3	6.2	2.7	8.5	2.2			
	17	Carp associations	1	4.7	2.2	6.9	2.7			
	18	Consumer group		3.9	2.1	5.6	2.6			

**Sample size (N) could slight differ per scored stakeholder, depending on the awareness or willingness of the stakeholders interviewed (21 total) to score the power and interest of certain stakeholders.*

[1] *Standard deviation*

[2] *Aggregated stakeholder category based on table 3.1*

[3] *Grouping information using the Tukey method and 95% confidence: Scored Aggregated cat. comparison for power and interest. Aggregated categories that do not share letter(s) in terms of power or interest are significantly different.*

3.3.2 Sustainability perceptions

In the following sections the sustainability perceptions of the stakeholders of the value chains of Norwegian Atlantic salmon and Polish common carp are considered.

Norwegian Atlantic salmon

The results below are divided into negative, positive, and uncertain sustainability perceptions. Generally, there were more positive (75) perceptions than negative (35). Uncertain (13) sustainability perceptions were mentioned the least. Stakeholders active in the grow-out, feed and R&D company mentioned most negative sustainability perceptions, whereas most positive sustainability perceptions were mentioned by stakeholders active in the grow-out, R&D company, processing and equipment producers answered more positively. The stakeholders from vet health management company mentioned the most uncertain sustainability perceptions.

The main negative sustainability perceptions were "salmon lice (terms of growth limitations and final product)" mentioned by the recreational tour guides (2x), R&D company and trainer institution (Table 3.7). This was followed up by the mention of "limited allowances/use of medicines and chemicals to combat diseases and parasites", which is also mentioned by the recreational tour guides (2x) and a certification body. Another important issue mentioned by the stakeholders from education and 2 R&D companies is the replacement of marine ingredients with plant ingredients, which could also influence the health and final nutritional quality of the fish. Additionally, government regulations were also perceived as negative by grow-out farmers (2x) and well-boat and transport.

Table 3.7: Count of negative sustainability perceptions, as highlighted by a variety of stakeholders in the Norwegian salmon value chain (N=36)

Negative Sustainability Perceptions (Total = 35)	**Count**
Salmon lice (terms of growth limitations and final product).	4
Limiting allowance/use of medicines and chemicals to combat diseases and parasites.	3
Marine ingredient replacement with e.g., plant ingredients can have negative effect on fish (weak health, nutritional etc.).	3
Regulations (government).	3
Feed (e.g., change in ingredients leads to change in nutrition and price).	2
Certification (e.g., ASC) - expensive and too much work and e.g., focus on social issues.	2
Intention of sustainability certification is questionable (seems to favour certain companies and size).	2
Operating costs increasing.	2
Salmon lice's interaction between farmed and wild salmon.	1
Escapees.	1
Conflict of interest with risk handling (sea lice treatment necessary but escapee risk).	1
Biological delousing with cleaner fish.	1
Environmental footprint.	1
Competition for space (e.g., fisher, anglers, tourism, cabin owners).	1
False perspectives towards sustainability (e.g., defecate in the sea is bad).	1
Interaction with community.	1
Strict measures (production, medicines, sea lice) to reduce impact on wild salmon (result; loss farm performance).	1
From food from the riches --> Staple food (should go lower in food chain).	1
NGO attacks (attacking our customers).	1
Black swan event (corona virus) disruptive to global markets.	1
Climate change.	1
Politics and governments (change could affect geopolitics and strength of customers).	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

The most positive perceptions (Table 3.8) concerned connection to the national electricity grid mentioned by the grow-out farmers (3x), a vet health management company, R&D company, and equipment producers (2x). This is followed up by perceptions of novel feed ingredients, mentioned by grow-out farmers (3x), trainer institution, equipment producers and an NGO. Finally, resource efficiency of Atlantic salmon production compared to terrestrial livestock, mentioned by egg and smolt production, primary processing, vet health management company and a certification body.

Table 3.8: Count of positive sustainability perceptions, as highlighted by a variety of stakeholders in the Norwegian value chain (N=36).

Positive Sustainability Perceptions (Total = 75)	**Count**
Connecting farms to main electricity net, less energy use.	7
Feed ingredients, sourcing, and novel feed ingredients (e.g., algae).	6
Resource efficiency (FCR) of the Atlantic salmon industry compared to e.g., protein from terrestrial meat.	5
Certification (e.g., ASC, MSC, GlobalG.A.P.) - third party assessment.	4
Recycling old equipment.	3
No/less/decrease anti-biotics.	3
Sea lice delousing system on well-boat (some of them using e.g., thermolicer, no chemicals).	3
Higher quality and bigger smolts (decrease mortalities, less sea lice because of shorter production on sea).	3
Technology (e.g., salmon lice laser, traceability of salmon through value chain).	3
Circular economy principles (zero waste) - use of by-products to increase value and feed output.	3
Sea lice combating strategies (coordinating fallow periods farms).	2
Land based (RAS).	2
Closed cage systems.	2
No/less use of anti-fouling (copper).	2
FM replacement (general) - reduce pressure on marine resources.	2
Efficient use of materials.	1
Waste management legislation.	1
Positive NGO campaigns (awareness of sustainable seafood).	1
Awareness of sustainability issues/challenges in the industry.	1
Less use of chemicals.	1
Biosecurity.	1
Cap on production.	1
Less interaction with wild fish.	1
Sea lice prevention systems (technology).	1
Improvement of fish welfare (including lumpfish).	1
Farm management.	1
Reduce benthic impact.	1
Developing salmon brood stock resistance against diseases.	1
Important food production sector (35 million meals a day).	1
Income for 30.000 people in Norway.	1
Reinvestment in coastal areas.	1
Certified marine ingredient use (IFFO RS, MSC).	1
FM replacement by plant ingredients.	1
FM and plant ingredient replacement by e.g., worms and mushrooms.	1
FIFO below 1.	1
Use of marine by-products.	1
Use of marine by-products (e.g., trimmings) in feed.	1
Environmental packaging.	1
Politics and governments increase pressure on sustainable production practices.	1
Global stability and peace.	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

The main uncertain sustainability perceptions (Table 3.9) concerned aquafeed ingredients, especially the health aspects of marine ingredient replacement, and the potential of novel ingredients, mentioned by smolt producers, a well-boat and transport and a vet health management company. This is followed by government enforced production limits, mentioned by the recreational tour guides (2x). Another uncertain sustainability perception was negative consumer perceptions, enforced by a bad media image, according to a primary processor and government authorities.

Table 3.9: Count of uncertain sustainability perceptions, as highlighted by a variety of stakeholders in the Norwegian value chain (N=36).

Uncertain Sustainability Perceptions (Total = 13)	**Count**
Aquafeed ingredients - plant ingredients (e.g., soy affects fish health), while real potential of novel ingredients (e.g., algae/insects) relatively unknown.	3
Production limits (government).	2
Consumer perception towards salmon (bad media image).	2
Strict regulations to combat sea lice.	1
Higher demands for production.	1
Fish welfare.	1
Skirts to prevent sea lice (less water refreshment for salmon --> diseases and health problems).	1
Lack of resources brings innovations and push sustainability.	1
Standards of ASC certification.	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

Polish common carp

The results below are divided into negative, positive, and uncertain sustainability perceptions (Tables 3.10 to 3.12). While for the Norwegian Atlantic salmon value chain, positive sustainability perceptions dominated, for the Polish common carp value chain counts of negative and positive perceptions were relatively similar with 35 and 34, respectively. Uncertain sustainability perceptions only accounted for 23. Stakeholders active in R&D, and education mentioned most negative, positive, and uncertain sustainability perceptions, as they were also more engaged in the exercise.

The top three negative sustainability perceptions concerned external factors, such as “climate change affecting water resource availability” mentioned by grow-out farmers, education (2) and carp associations. Lack of water to fill up ponds was mentioned specifically by education (2x) and R&D institute (2x). “Dependency on subsidies” was mentioned by R&D institutes (3), and there was a negative perception of carp farming created by NGOs, mentioned by feed companies, education, and a R&D institute. Other concerns related to welfare issues concerning the sale of live carps, mentioned three times by different interviewees by an NGO.

Table 3.10: Count of negative sustainability perceptions, as highlighted by a variety of stakeholders in the Polish value chain (N=22).

Negative Sustainability Perceptions (Total = 35)	**Count**
Climate change (e.g., relation to water availability/sources).	4
Lack of water to fill up ponds (incl. water access restrictions).	4
Dependency on subsidies.	3
NGO activities (creating a negative impression of carp farming and consumption).	3
Live carp sales.	3
Lack of governmental subsidies.	2
Animal predation (low water surface makes problem worse).	2
Import of fishes (Czech Republic), influence on price significant.	2
Mass production to meet supply in December (leads to bad quality).	2
Market changes (rapid change to processed carp).	1
New risk factors due to globalisation (diseases, fish, transportation).	1
Price of water to fill ponds.	1
The way we produce (organic) – diseases are easily transmitted into the ponds by e.g., birds.	1
Media - Negative public messaging about carp farming in Poland.	1
COVID-19 affects supply chain (low orders).	1
Fisher got money from EU, so they do not fish.	1
Processors cannot keep up with new innovations (new packaging, processing line) required by hypermarkets.	1
Decrease of freshwater fish consumption.	1
Decrease in interest in fisheries education.	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

The top three positive issues included the EU funding, mentioned by education (3x) and R&D institute (2x) (Table 3.11). Increased processing capacity was mentioned by a tour guide, R&D institute (2x) and NGO. The traditional extensive Polish production system was mentioned by stakeholders active at the grow-out farms, feed, R&D institute, and in a carp association.

Table 3.11: Count of positive sustainability perceptions, as highlighted by a variety of stakeholders in the Polish value chain (N=22).

Positive Sustainability Perceptions (Total = 34)	**Count**
EU funds for innovation/diversification/fisheries/aquaculture support programs and external assistance.	5
Increase in output of (primary) processing sector.	4
Extensive production - sustainable (in balance with nature/eco-friendly). Limiting waste, little energy use (slow food products etc.).	4
Climate change (e.g., shorter growth season, water shortages).	3
Diversification of income.	3
Market changes (rapid change to processed carp).	1
Inclusion of fishponds in small water retention programs.	1
Extensive use of ponds complexes as recreational and ecological education objects.	1
Presence of universities and institutes conducting research for fisheries sector.	1
Increase in production (efficiency).	1
Locked potential of carp by e.g., processing fish into more convenient food (smoked, fillets, sausages), up cycling by-products (he did his MSc in this field), polyculture with other species and by developing activities that are related to carp farming (education, birdwatching, etc.).	1
Sustainable local feed ingredients (weed and corn - low carbon footprint).	1
Water environmental program Poland (EU fishery funds) gives money to carp farmers (they need to meet demands for natural areas to get this money).	1
Improve feed formulations. Stop using soy from South America. Low impact as possible.	1
Out of season spawning (keep carp on market all year around).	1
Short food supply chain.	1
Circular economy in aquaculture.	1
Fast exchange of information (digitalisation).	1
Coopetition (building the social capital, sharing economy).	1
New packaging (MAP packaging) vacuum, to deliver fresh and without icing in coming 5 years.	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

The top three uncertain sustainability perceptions included climate change linked temperature rises, mentioned by health and education (2x) (Table 3.12). Additionally, education (2x) mentioned that national regulations are not keeping up with R&D development in the sector. One of these laws is the "*Ustawa z dnia 20 lipca 2017 r. - Prawo wodne [Water Law], (consolidated text Dz.U. 2017, item. 1566) (KancelariaSejmu, 2017)*" that creates an upper-limit of fish growth at 1,500 kg ha^{-1} year^{-1}. This limit is the threshold to receive environmental subsidies, but farmers can still produce more if they wish, but they would not get water-environmental compensations and would need to pay for wastewater released to the river (Eljasik, 2022). Another uncertainty perception concerned consumer preference, which is in line with uncertainty around product form, both mentioned by two stakeholders from an R&D institute. Another important sustainability uncertainty was the slaughter process of live carp, which was perceived to result in suffering, according to two NGOs (2x).

Table 3.12: Count of uncertain sustainability perceptions, as highlighted by a variety of stakeholders in the Polish value chain (N=22).

Uncertain Sustainability Perceptions (Total = 23)	**Count**
Climate change (positive/negative trade-offs of rise in temperature, possible fish growth).	3
Policy (national regulations often cannot keep up with R&D, so functions as bottleneck).	2
Consumer preferences relatively unknown.	2
Market changes (form of product presentation).	2
Live carp not always slaughtered properly (suffering).	2
Subsidy to maintain natural area (natura2000), not sufficient to pay costs.	1
Fish farming gets more dependent on public money.	1
Extensive carp farming not sufficient to pay costs.	1
Prices of table fishes.	1
Weather and water conditions.	1
New technology.	1
Unknown if carp farmers will be included in new water management framework of the government (this prioritises water users based on needs).	1
Lack of water from the river to fill up ponds.	1
Lack of water retention (from precipitation).	1
Eco-groups demanding no sale off for live carp. Could be option for processing.	1
Not sure if feed use is eco-friendly unless by-products are used.	1
Government laws forbid sales of live carp, but vet guidelines allowed. Confusion!	1

In red most important sustainability factors, orange middle range and in yellow less important sustainability factors.

3.3.3 Awareness of the innovations

In the following sections the perceptions towards the innovations are presented, starting first with Norwegian Atlantic salmon, followed up by Polish common carp (Table 3.13 and 3.14).

Norwegian Atlantic salmon

The Atlantic salmon industry in Norway shows a high interest and confidence in the use of big data (variety of data arriving in large volumes from different devices (IoT)) for farm management and welfare (Table 3.13). Additionally, novel feed ingredients, such as microalgae, insect proteins, macroalgae, by-product meals and hydrolysates, and single cell protein show potential for implementation because of the stated alignment with the collective views of stakeholders, as people showed awareness of the benefits for their company/industry.

Overall, the GAIN innovations were scored quite similarly across the different aggregated groups (Table 3.13). However, “(12) by-products for cosmetics/nutraceuticals” shows significant differences between “research” and “others”, and “producers”, and “supporting” category.

Table 3.13: Awareness/interest in sustainable intensification measures in Norway. Aggregated categories were compared using the Tukey method (95% confidence) – Means that do not share letter(s) are significantly different in their attitudes towards innovations (N=33).

Innovations[1]		**Avg**[2]	**SD**[3]	**Producers**	**Research**	**Others**	**Supporting**
1	**Use of big data for welfare**	5.52	0.87	A	A	A	A
2	**Use of big data management and support**	5.27	1.23	A	A	A	A
3	**Microalgae as a feed ingredient**	5.21	1.78	A	A	A	A
4	**Insect protein as a feed ingredient**	5.21	1.65	A	A	A	A
5	**Macroalgae as a feed ingredient**	5.15	1.56	A	A	A	A
6	**Processing salmon by-products for feed**	5.15	1.50	A	A	A	A
7	**Hydrolysed fish proteins**	4.61	1.78	A	A	A	A
8	**Single cell proteins**	4.24	2.17	A	A	A	A
9	**Sludge for biogas (as a green energy source)**	4.00	1.95	A	A	A	A
10	**Mortalities for biogas**	3.97	1.91	A	A	A	A
11	**Sludge for fertiliser**	3.73	2.32	A	A	A	A
12	**By-products for cosmetics/nutraceuticals**	3.70	2.05	A	AB	AB	B
13	**Shells for biofilters**	2.48	2.20	A	A	A	A
14	**Shells for cement/filler**	1.24	1.90	A	A	A	A
15	**Shells for packaging**	1.09	1.93	A	*	A	A

[1] First column, "grey" is precision aquaculture, "green" are novel feed ingredients, "blue" are by-products and circular economy. Descriptions of the GAIN innovations in Table 3.2.
[2] In green (average score between 4.5-6), orange (3-4.5), yellow (1.5-3) and red (0-1.5).
[3] Standard deviation
**No responses for this category*

Polish common carp

The common carp industry shows less interest in external innovations (Table 3.14) compared with Atlantic salmon in Norway (Table 3.13) and their relative importance was perceived differently. In Norway, feed was considered most important, which was not the case in Poland and likely linked to the natural extensive production characteristics of the sector that require little to no feed. However, there is supplementary feeding and there is relatively high interest to increase production using certain external innovations, such as the medium interest expressed to use processed carp by-products for feed, cosmetics and nutraceuticals, and sludge for fertilizer. Additionally, there was also medium interest in novel ingredients, such as insects, micro- and macroalgae and hydrolysed fish protein. There is relatively low interest in "big data management support".

The innovations are scored quite similarly across the different aggregated groups (table 3.14). However, “(2) sludge for fertiliser” shows significant differences between “producers” and “research”, and “others” and “supporting”.

Table 3.14: Awareness/interest in the sustainable intensification measures in Poland. Aggregated categories were compared using the Tukey method (95% confidence) – Means that do not share letter(s) are significantly different in their attitudes towards innovations (N=15).

Innovations[1]		**Avg[2]**	**SD[3]**	**Producers**	**Research**	**Others**	**Supporting**
1	**Processing carp by-products for feed**	4.40	1.76	A	A	A	A
2	**Sludge for fertiliser**	3.87	2.45	AB	A	B	B
3	**By-products for cosmetics/nutraceuticals**	3.60	2.32	A	A	A	A
4	**Insect proteins**	3.53	1.77	A	A	A	A
5	**Microalgae**	3.13	1.96	A	A	A	A
6	**Macroalgae**	3.00	1.96	A	A	A	A
7	**Sludge for biogas (as green energy source)**	2.80	1.97	A	A	A	A
8	**Use of big data management and support**	2.80	2.40	A	A	A	A
9	**Use of big data for welfare**	2.67	2.50	A	A	A	*
10	**Hydrolysed fish proteins**	2.60	2.20	A	A	A	A
11	**Mortalities for biogas**	1.80	1.93	*	A	A	A
12	**Single cell proteins**	1.27	1.28	A	A	A	A
13	**Shells for biofilters**	0.93	1.88	*	A	*	A
14	**Shells for packaging**	0.93	2.18	*	A	*	B
15	**Shells for cement/filler**	0.80	1.88	*	A	*	A

[1] First column, “grey” is precision aquaculture, “green” are novel feed ingredients, “blue” are by-products and circular economy. Descriptions of the GAIN innovations in Table 3.2.

[2] In green (average score between 4.5-6), orange (3-4.5), yellow (1.5-3) and red (0-1.5).

[3] Standard deviation

**No responses for this category*

3.3.4 Delphi survey - consensus and disagreements on industry perceptions

The first round of the Delphi was distributed through a survey format (Appendix A1.3 – A1.4) in February 2021 to as many stakeholders that also participated in the initial KI of the Norwegian Atlantic salmon and Polish common carp value chain. A few stakeholders were newly introduced to the first Delphi round to increase the sample size through promotion of the survey in aquaculture societies, project partner's network in Norway, Poland, and wider Europe. The individual answers from the panel of experts were analysed, aggregated, and anonymized to inform a second-round list of questions (Appendix A1.5 – A1.6), which was distributed in June 2021 to the stakeholders that participated in the first Delphi round. Like the first Delphi round, stakeholders were newly introduced to the second Delphi round to increase the sample size (Table 3.15).

The answers from the two Delphi rounds were used to establish a clear variation and/or consensus around different issues in the industry. Results that include a scoring system are visualised by a bar in the graph which indicates the average score, while the error bars indicate the minimum and maximum score that was provided by the participants. The answers were then matched with the initial KI surveys to identify similarities and differences in opinions. In the following sections the key outcomes regarding industry perceptions, trends, legislation, sustainability, and growth are presented.

Table 3.15: Number of industry responses from different stakeholders in two Delphi rounds.

Value chain actors/stakeholders	**Aggregated category**	**Delphi Round**			
		Norwegian Atlantic salmon		**Polish common carp**	
		1 (n=11)	**2 (n=11)**	**1 (n=15)**	**2 (n=12)**
Stakeholders in initial KI and Delphi (round I)		**7/11**	**4/11**	**13/15**	**9/12**
Brood stock/hatchery	Producers		1		
Farm		3	1	2	1
Slaughterhouse and processing			1	1	
Feed	Supporting	2	3	1	1
Vet/health			1	1	1
Trade			1		
Equipment producers		1			
Recreational	Others			1	
Education, research, and academia	Research	3	2	9	5
NGO	Others				1
Certifiers		2			
Government					1
Other			1		2

3.3.4.1 Delphi round 1

In this section the responses from the panel of experts are discussed regarding industry perceptions (e.g., general trends, sustainability) legislation perceptions (EU, national and regional legislation regarding sustainable intensification and environmental sustainability), sustainable intensification support strategies and scoring of the most important sustainability indicators.

Industry perceptions

This section is focussing on the industry perceptions, such as general trends and sustainability. Additional it compares perceptions of industry stakeholders towards their own industry and these stakeholders' perceptions of the public towards their industry (Appendix A1.3 and A1.4, respectively).

Norwegian Atlantic salmon

The results indicate an interest in increasing the production volume in a sustainable way (Figure 3.6a). This is in line with the identified key aspects of the environmental sustainability of the industry such as the use of sustainable feeds, technically efficient production, and importance of high fish welfare, as perceived by the expert group (Figure 3.6b). While the people in Norway have the perception that people outside Norway considered the Norwegian industry as sustainable (Figure 3.6d), the Norwegian panel of experts indicated are neutral standpoint on the idea that the Norwegian industry was "already sustainable" (Figure 3.6c). This explains the panel of experts' interest in "increasing responsible production" and "key aspects" of the environmental sustainability of the Norwegian industry (Figure 3.6a and b, respectively).

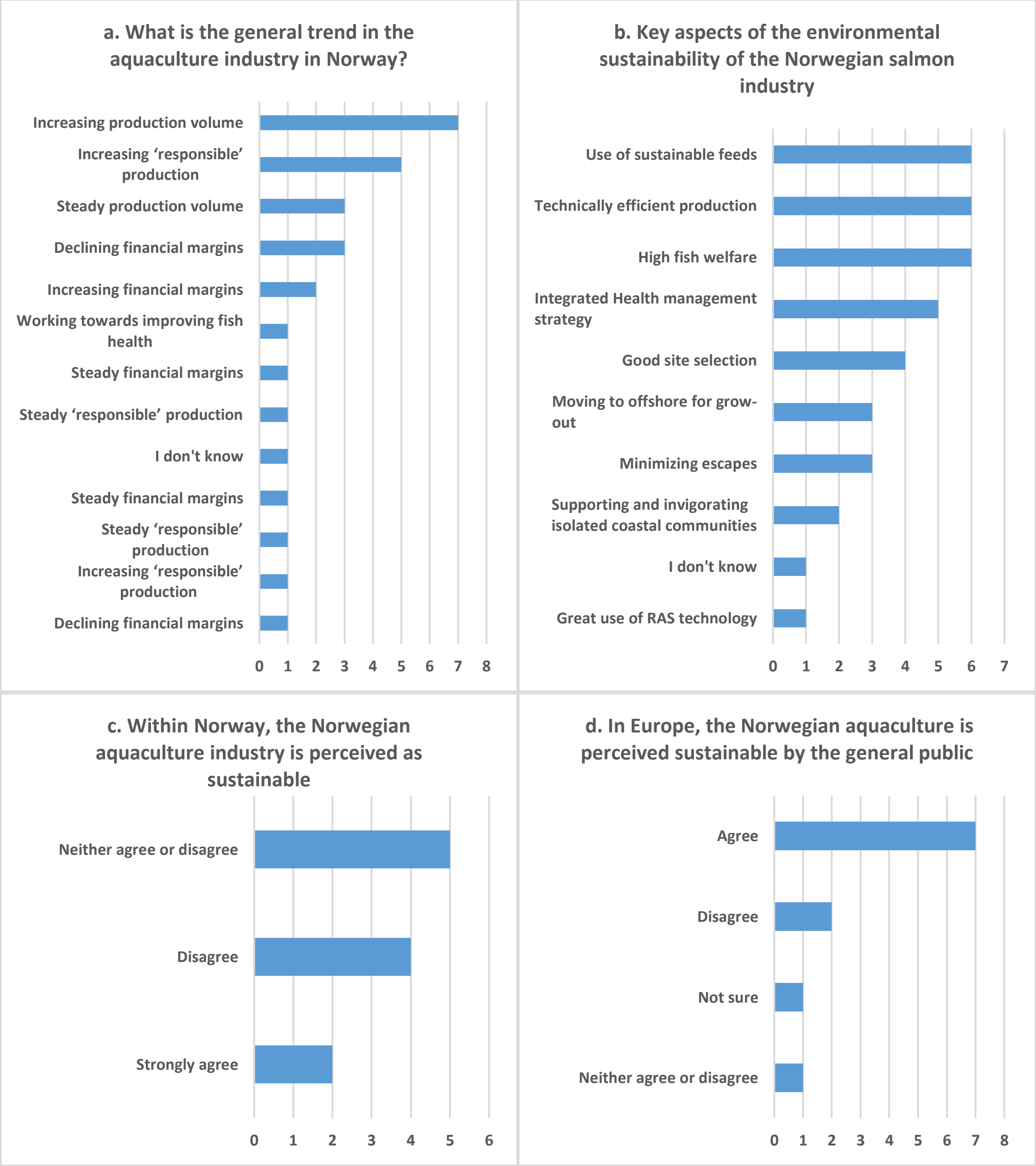


Figure 3.6a-d: Industry and sustainability perceptions for Norwegian Atlantic salmon (a-b multiple choice, c-d likert scale, n=11).

Polish common carp

The panel of experts showed a general trend of "steady production volumes" and "declining financial margins" (Figure 3.7a). Most stakeholders highlight that the "low impact" and "natural and traditional production" are aspects of the industry that should be promoted (Figure 3.7b). This is also in line with the sustainability perception of the Polish panel of experts, as they indicated a consensus on the idea that the Polish common carp industry is already sustainable, while they also indicate "not to have an opinion" regarding people outside Poland perceiving the Polish common carp industry as sustainable (Figure 3.7c and d, respectively).

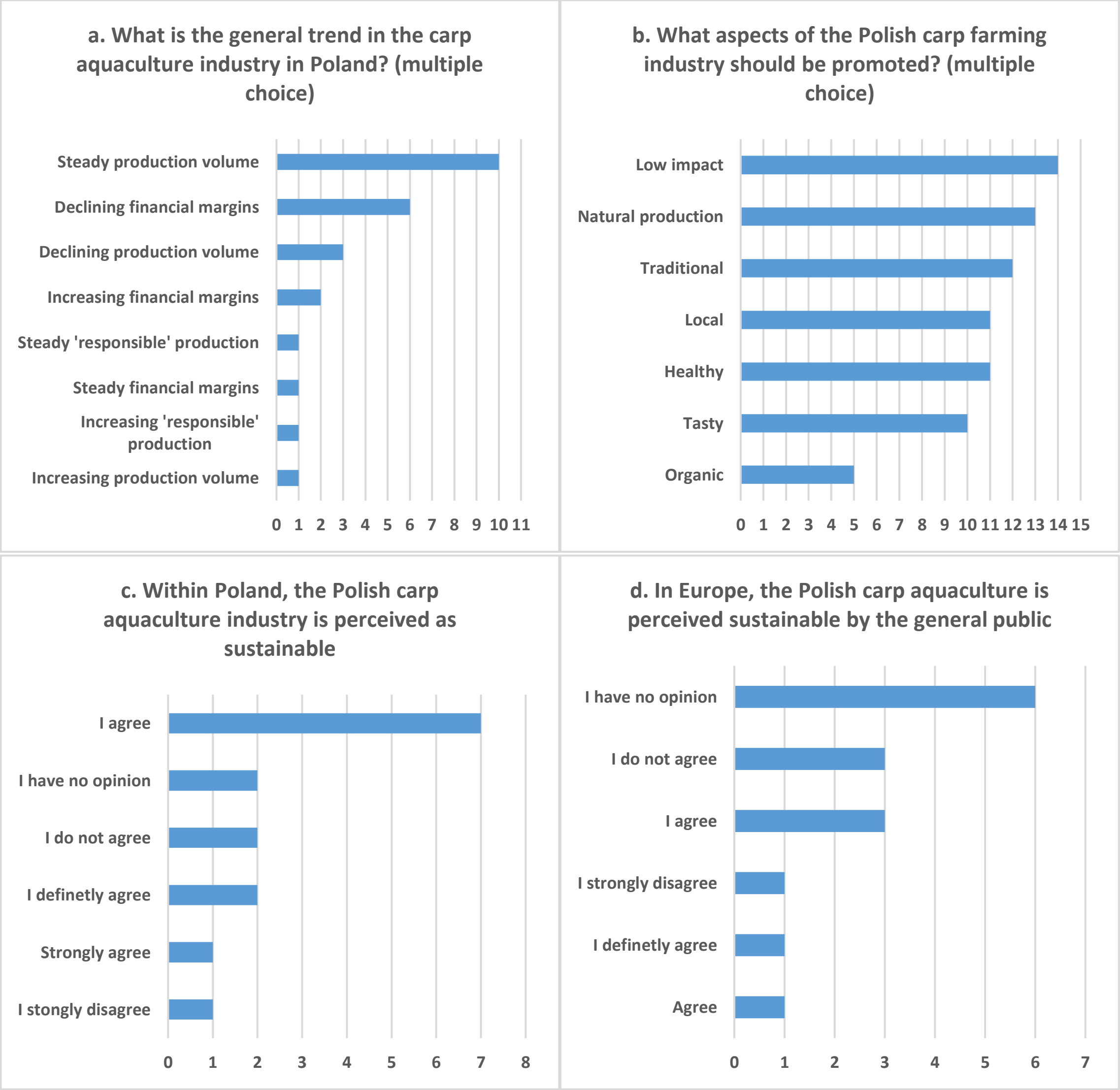


Figure 3.7a-d: Industry and sustainability perceptions for Polish common carp (a-b multiple choice, c-d likert scale, n=15).

Legislation perceptions of the industry

This section is focussing on legislation perceptions regarding supporting the industry growth and environmental sustainability from an EU, national and regional legislation level.

Norwegian Atlantic salmon

The panel of experts neither agreed or disagreed or were not sure on the matter that EU legislation is supporting growth (Figure 3.8a). However, there is a consensus that EU legislation supports the industry to become more environmentally friendly (Figure 3.8b). National legislation on industry growth and environmental sustainability are supportive according to most stakeholders within the panel of experts group (Figure 3.8c and d). When it comes to regional legislation supporting the growth of production volume output, opinion is divided between “neither agree or disagree”, “agree” and “strongly agree”, while the panel of experts seem to agree that these regional polices are supportive to become more environmentally friendly (Figure 3.8e and f).

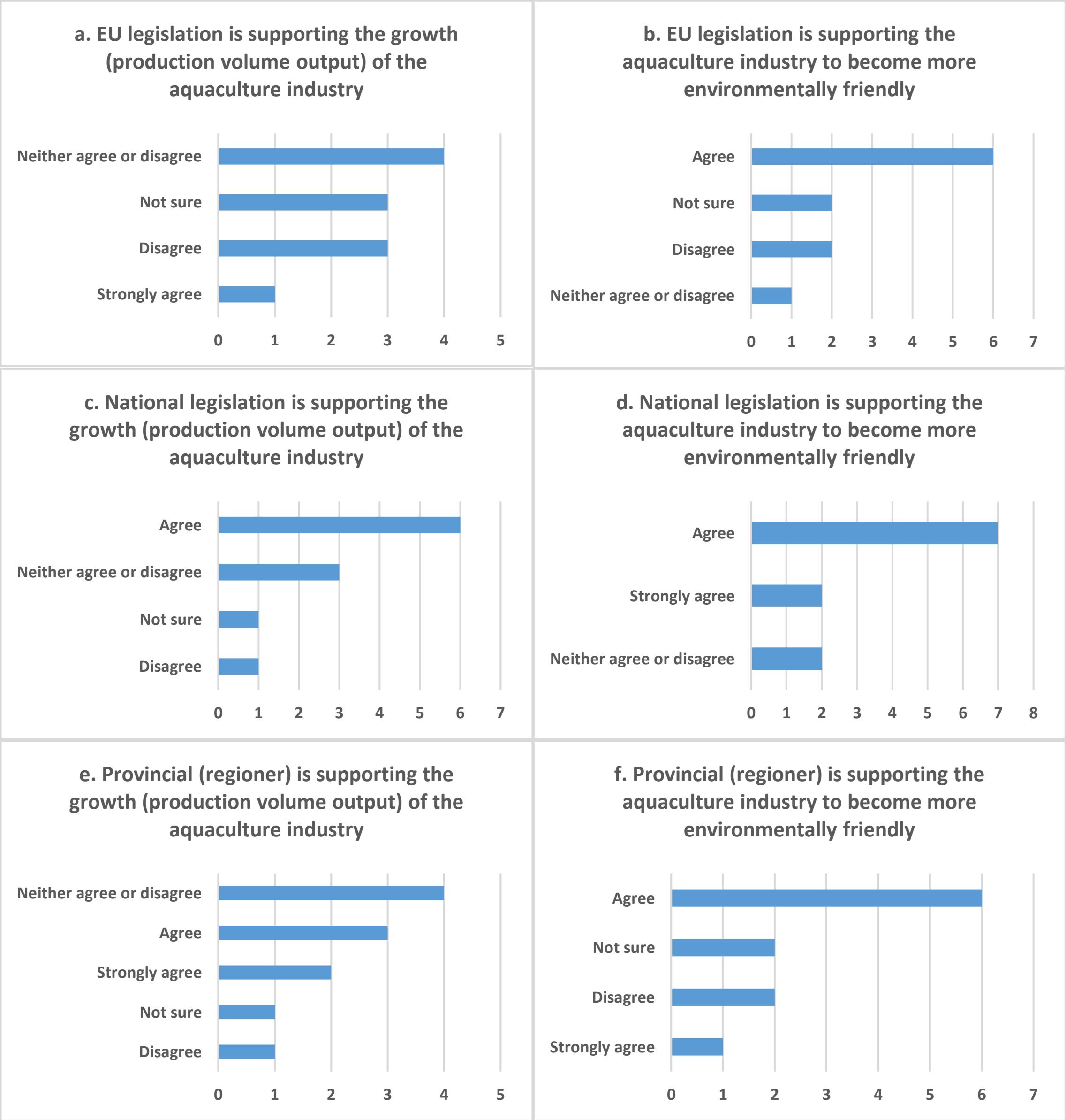


Figure 3.8a-f: EU, national and provincial legislation perceptions of the Norwegian Atlantic salmon industry (likert scale, n=11).

Polish common carp

The opinion of the panel of experts is divided when it comes to EU legislation supporting the growth of the industry, while a large part of the panel of experts “agrees” that EU legislation supports the industry to become more environmentally sustainable (Figure 3.9a and b, respectively). In contrast national legislation was perceived as being unsupportive of growth, while the panel of experts indicated uncertainty in terms of its support for the industry to become environmentally sustainable, by showing a mixed response “I do not agree” and “I have no opinion” (Figure 3.9c and d). This uncertainty was applicable to the perception of regional legislation being supportive for growth and environmental sustainability, as indicated by the panel of experts showing “not to have an opinion” and “I do not agree” on this matter (Figure 3.9e and f).

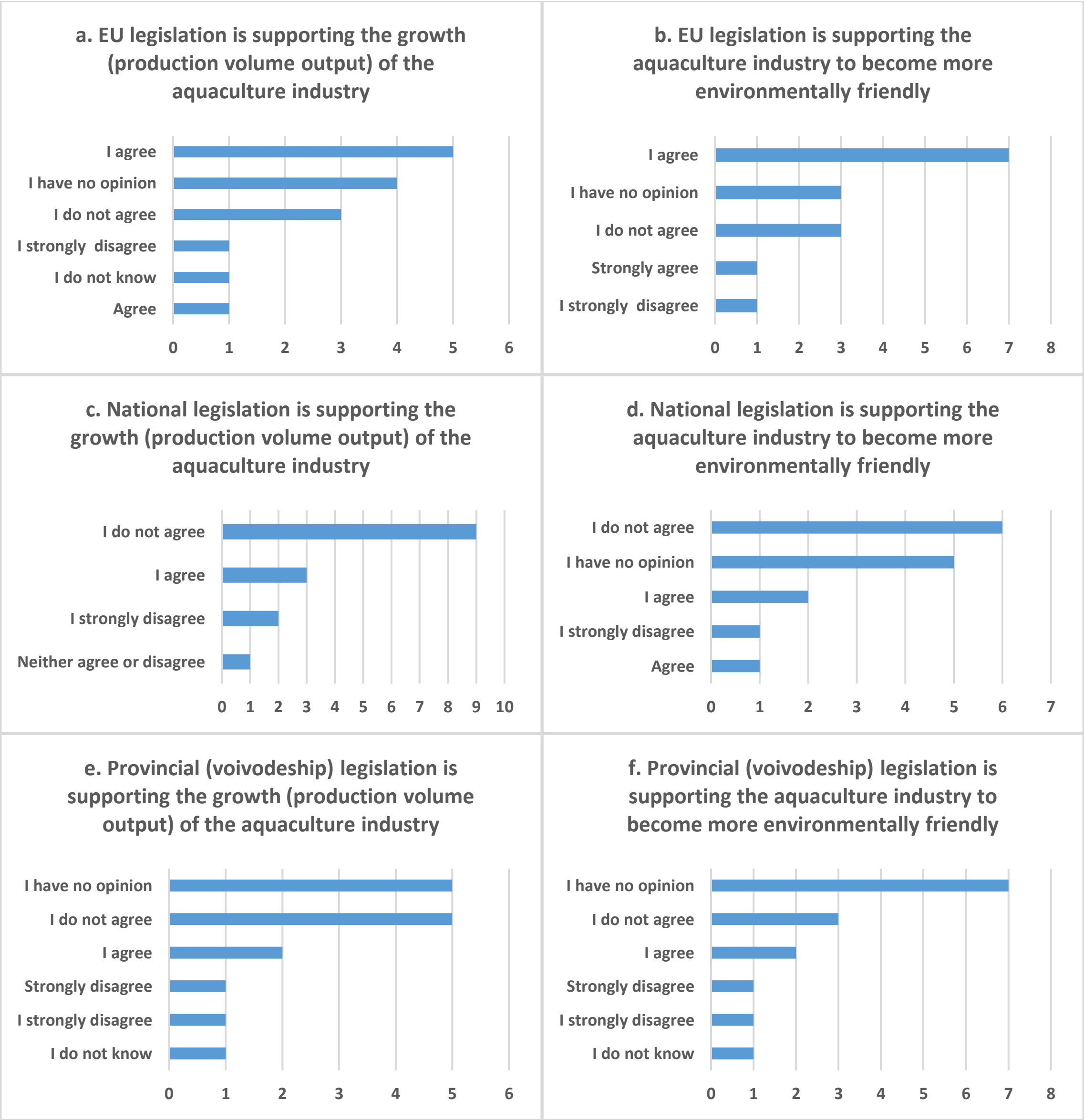


Figure 3.9a-f: EU, national and provincial legislation perceptions of the Polish common carp industry (likert scale, n=15).

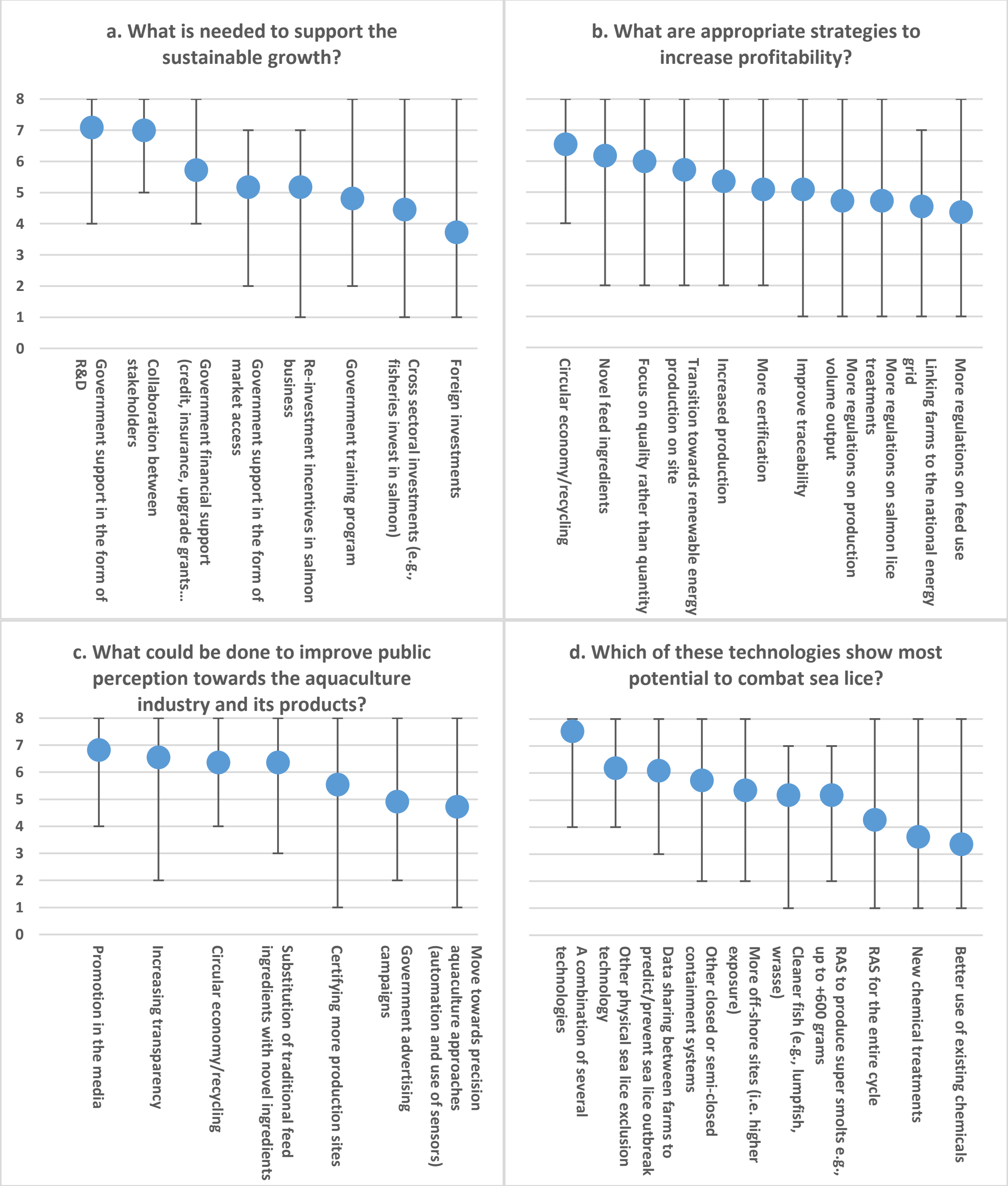
Sustainable intensification support

This section is focussing on strategies to support sustainable intensification, such as regulations, collaboration, investments, technologies, improving public perception, strategies to combat sea lice.

Norwegian Atlantic salmon

There was an overall consensus among the panel of experts that "government support in the form of R&D" and "collaboration between stakeholders" are needed to support sustainable intensification of the Norwegian aquaculture industry (Figure 3.10a). In terms of strategies, the panel of experts showed a clear consensus on the adoption of "circular economy/recycling principles". This was followed up using "novel feed ingredients", and a need for a "focus on quality rather than quantity" (Figure 3.10b). When it comes to the improvement of public perception towards aquaculture and its products, "media promotion", "increasing transparency", "circular economy/recycling principles" and the "substitution of traditional feed ingredients with novel feed ingredients" are considered suitable strategies (Figure 3.10c).

Sea lice is considered a large sustainability challenge. Suitable mitigation strategies are a "combination of several technologies", "other physical sea lice exclusion technologies" and "data sharing between farms to predict/prevent sea lice outbreak" (Figure 3.10d).



a. What is needed to support the sustainable growth?

b. What are appropriate strategies to increase profitability?

c. What could be done to improve public perception towards the aquaculture industry and its products?

d. Which of these technologies show most potential to combat sea lice?

Figure 3.10a-d: Perceptions towards sustainability, profitability, public perception, and sea lice control (Score: 1 low potential/not important, 8 high potential/important). Error bars indicate the min and max score that was provided by the participants (n=11).

The panel of experts identified the importance for novel feed ingredients to support environmental sustainability, improve feed efficiency, fish welfare and public consumer perceptions towards farmed fish. There was a consensus that most novel feed ingredients have potential to improve sustainability, feed efficiency, fish welfare and public consumer perceptions, with "plant ingredients" showing the lowest potential of all ingredients (Figure 3.11a-d). The panel of experts showed a clear consensus on the potential of "marine ingredients from fishery processing by-products" to improve environmental sustainability, feed efficiency and fish welfare (Figure 3.11a, b and c, respectively).

Additionally, these ingredients also showed potential to improve the "public consumer perception of farmed fish", whereas the panel of experts put this ingredient on the second place after "microalgae" (Figure 3.11d). While "marine ingredients from fishery processing by-products" and "microalgae" show the highest preference to improve feed efficiency, fish welfare and public perception (Figure 3.11b, c and d, respectively), insect protein and seaweed were also listed in the top 3 to support sustainability, feed efficiency, fish welfare and improve the public perception towards farmed fish (Figure 3.11a-d).

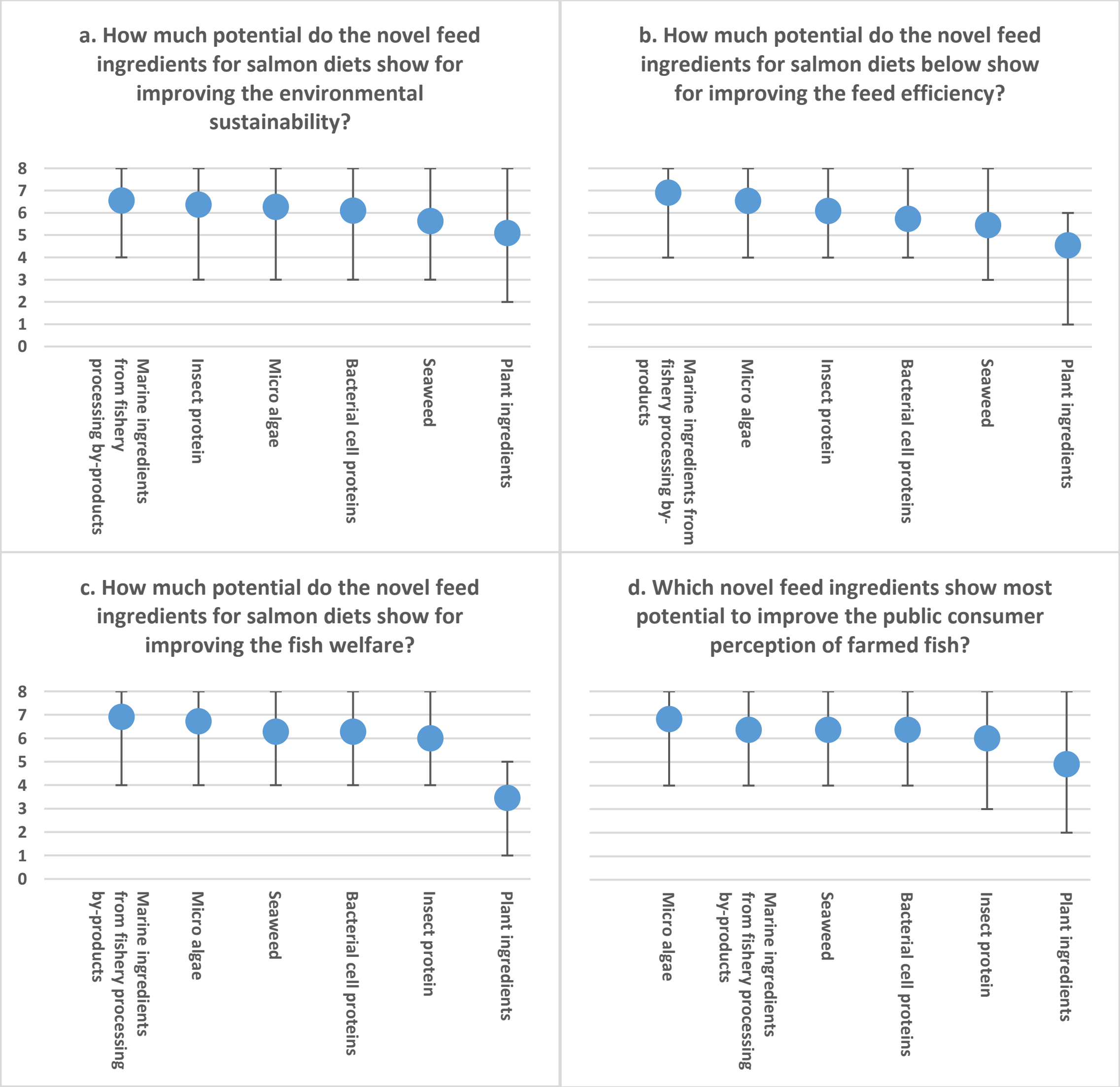


Figure 3.11a-d: Novel feed ingredients to support sustainable intensification of Norwegian Atlantic salmon (Score: 1 low potential, 8 highly potential). Error bars indicate the minimum and maximum score that was provided by the participants (n=11).

Polish common carp

The panel of experts indicated a consensus around needs to support the sustainable intensification, such as “collaboration between stakeholders”, “EU funds” and “government support in the form of R&D” (Figure 3.12a). In terms of suitable mitigation strategies against the effect of climate change, the panel of experts showed an overall preference for the “efficient use of water resources”. However, there was disagreement among the panel of experts in terms of the importance of “efficient use of water resources”, visualised by the large error bar indicating the minimum and maximum score provided (Figure 3.12b).

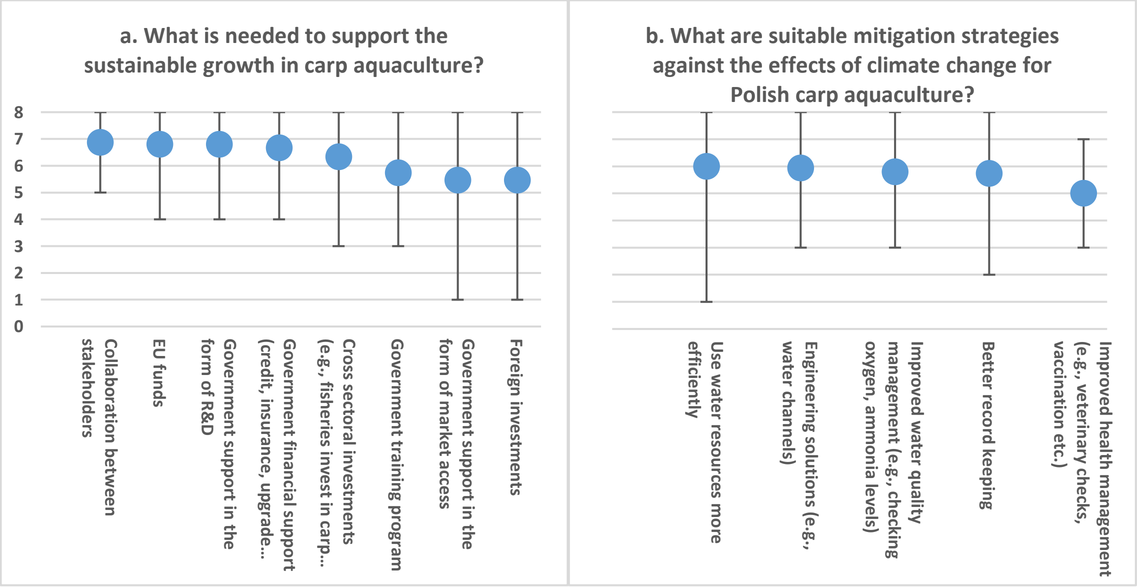


Figure 3.12a-b: Sustainable intensification support and climate change resilience for the Polish common carp industry (Score: 1 not important, 8 highly important). Error bars indicate the minimum and maximum score that was provided by the participants (n=15).

In terms of actions to improve public perception towards the aquaculture industry, the panel of experts showed a preference for “more human control of other predators” and “certifying more production sites”, while showing uncertainty around the importance of these actions as indicated by the minimum and maximum score provided (Figure 3.13a). Nevertheless, the panel of experts showed a clear consensus towards a media promotion strategy to improve perceptions of the industry (Figure 3.13b). “Increasing awareness”, “more education”, and even “more processing” was considered appropriate strategies to improve the image of carp farming (Figure 3.13c). In this regard, it was considered important to increase the year around appeal for carp and the panel of experts showed a clear consensus on “consumer perception change” and “diversifying carp products (increase processing)”. In addition, “marketing and advertising campaigns” and “organizing promotion events” could also be an appropriate strategy to increase the year around appeal for carp (Figure 3.13d).

Figure 3.13a-d: Support to overcome consumer perceptions towards the Polish common carp industry (Score: 1 not important, 8 highly important). Error bars indicate the minimum and maximum score that was provided by the participants (n=15).

The panel of experts showed a preference for “diversification of activities at the farm”, “efficient predator control” and “increase processing” as appropriate strategies to increase the profitability of the carp industry (Figure 3.14a). More specifically, they showed a clear consensus regarding “increased processing”, indicated by the small range of the minimum and maximum score provided. This was confirmed by an overall agreement when the panel of experts were asked directly if carp processing could increase the profitability of the industry (Figure 3.14b). They also identified “fillets” as the most profitable carp product, followed up by “traditional (live) carp” indicating uncertainty among the panel of experts and “carp sheets” (Figure 3.14c). However, the panel of experts indicated that a “change in consumer perceptions”, “diversifying the market” and “subsidies or incentives” are required to intensify carp processing (Figure 3.14d).

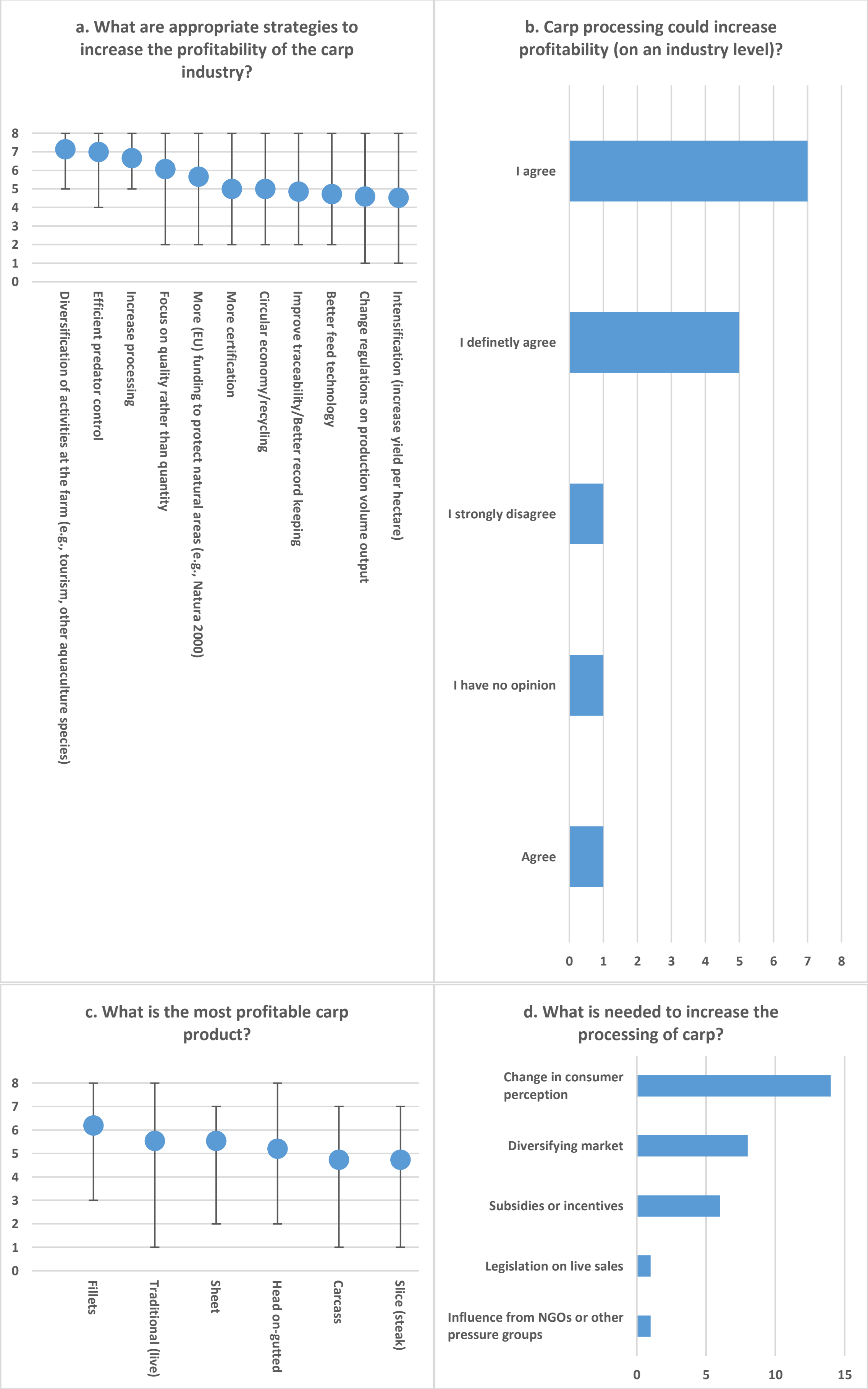


Figure 3.14a-d: Carp processing (a scoring; b likert scale; c scoring; d multiple choice). Score: 1 low potential/profitability, 8 highly potential/profitability, error bars indicate the min and max score provided by the participants (n=15).

Scoring of the most important sustainability indicators

The panel of experts from Norway and Poland were asked to score the relative importance of the individual socio-economic and environmental sustainability indicators as part of the Eco-intensification Sustainability Index (EISI) (Newton *et al.*, 2021b). While most listed indicators of the EISI in the result section speaks for itself, some need explanation as show in Table 3.16.

Table 3.16: Impact indicators (environment, socio-economic and fish welfare) and description.

Impact indicator*	**Description**
Feed efficiency	Efficiency of fish to convert feed into body weight
Greenhouse gases/carbon footprint	Total amount of greenhouse gases produced
Nutrient release in the environment	Covers the nutrients and minerals that could potentially be released in aquatic systems, potentially causing algae bloom in surface water (eutrophication)
Fish In : Fish Out	Represents the amount of fish used to produce 1 kg of farmed fish.
Benthic impact	Impact on the bottom of a body of water
Oxygen demand (BOD/COD)	Biological Oxygen Demand (BOD): Amount of oxygen needed to break down organic material. Chemical Oxygen Demand (COD): Amount of oxygen required to break down the organic material via oxidation.
Suspended solids in the water column	Particles in the water column
Acidification	Covers the gasses released in the production causing a decrease in the ocean’s pH (more acid).
Land footprint	Covers the land use per annum
Labour and wage structure	Labour and wage distribution of operation
Number of employees per unit output	Full-time equivalents per metric tonne of production
Output value per employee	Revenue divided by the amount of employee
Cleaning of the nets	Frequency of net cleaning (applicable to Atlantic salmon)
Average stocking density	Amount of fish (kg) per surface/volume of water
Amount of emergency harvests	Amount of emergency harvests in a year because of e.g., disease outbreak

**Certain impact indicators are only applicable to a specific value chain.*

Norwegian Atlantic salmon

A similar distribution of the average score range of the individual indicators is observed within the economic, environmental, social and fish welfare categories, indicating the importance of a wide range of indicators to assess sustainability, according to the panel of experts (Figure 3.15 and 3.16).

Regarding the economic indicators, the panel of experts scored the highest relevance to “feed efficiency”, followed up by “fish mortality at the farm” and “farm operating costs” (Figure 3.15a). “Feed efficiency” was also considered the second most important environmental indicator after “recycling of by-products in other industries”. This was followed up by “greenhouse gases” and “nutrient release in the environment” (Figure 3.15b).

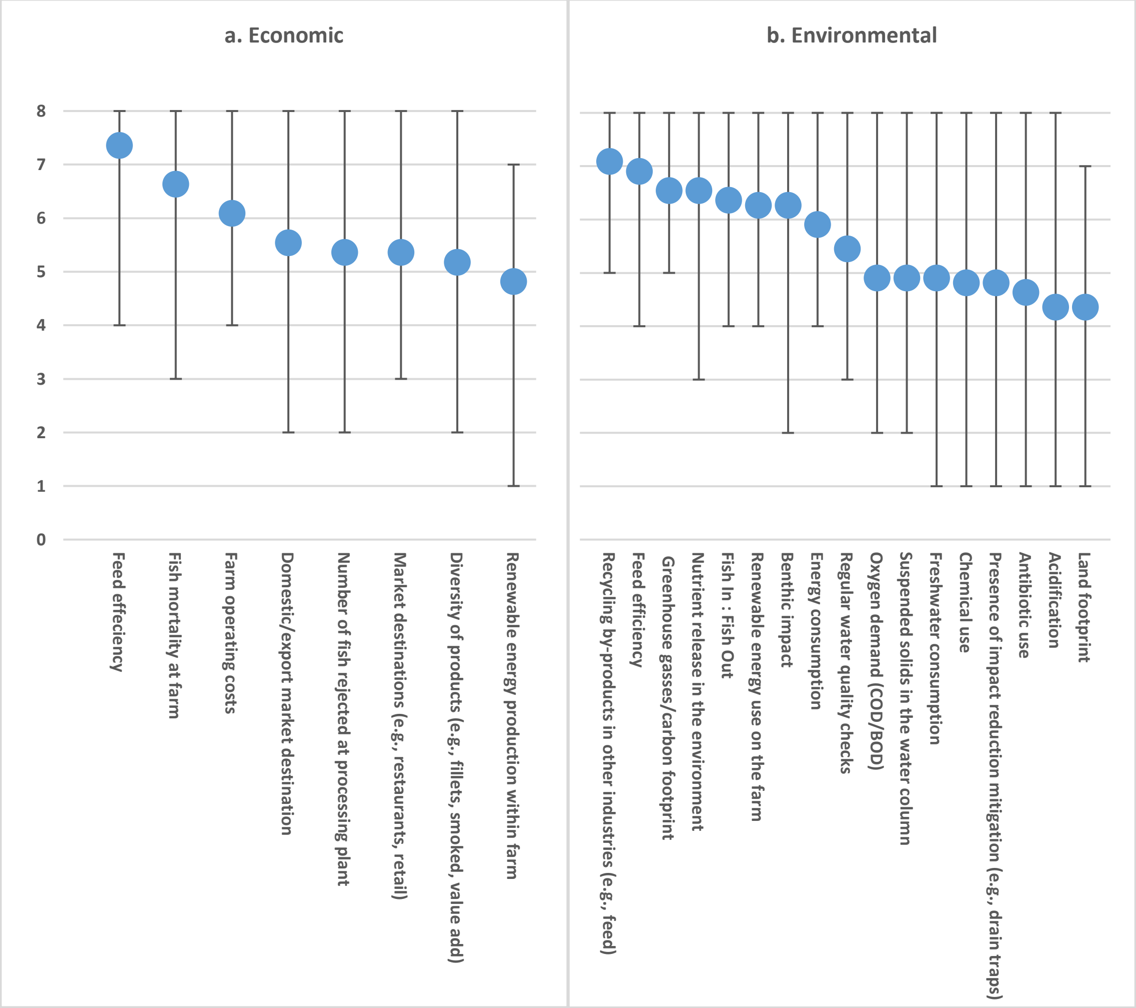


Figure 3.15a-b: Relevance scoring of the a) economic and b) environmental sustainability indicators of Norwegian Atlantic salmon (score: 1 low importance, 8 high importance). Error bars indicate the min and max score provided by the participants (n=11).

The expert group scored "employee safety and risk reduction", "risk exposure to hazardous/chemicals" and "labour and wage structure", as the most important social sustainability indicators (Figure 3.16a). When it comes to the fish welfare, "fish welfare training for employees", "health management plan", and "number (%) of farm mortalities in cycle", are considered the most important indicators (Figure 3.16b).

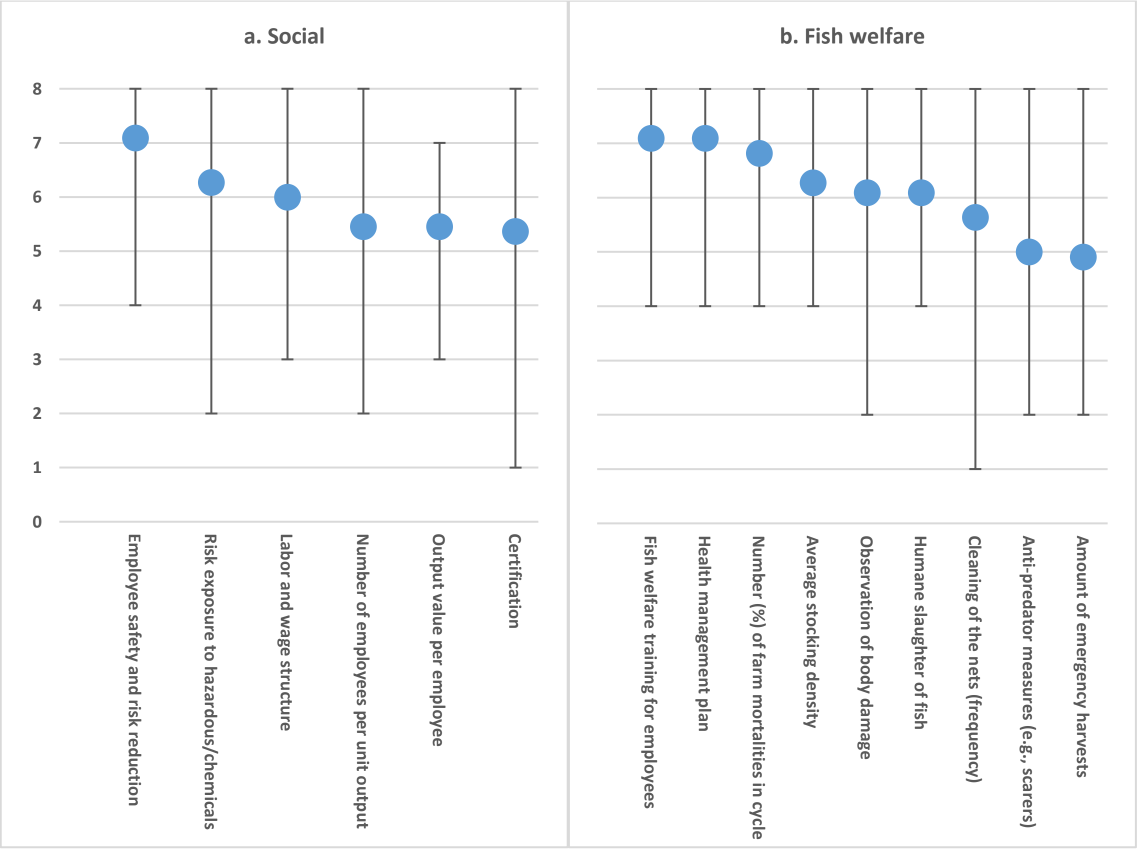


Figure 3.16a-b: Relevance scoring of the a) social and b) welfare indicators of Norwegian Atlantic salmon (score: 1 low importance, 8 high importance). Error bars indicate the min and max score provided by the participants (n=11).

Polish common carp

A similar distribution of the average score range of the individual indicators is observed within the environmental, social and fish welfare categories (Figure 3.17 and 3.18). The economic category showed slightly higher upper values (Figure 3.17a). Overall, the scoring of the indicators by the panel of experts highlighted the importance of a wide range of indicators to assess sustainability.

The expert group considered the “diversity of products and market destinations” and the “farm operating costs” as the most important economic sustainability indicators (Figure 3.17a). When it comes to the environmental sustainability, “land footprint”, “regular water quality checks” and “freshwater consumption” are considered the most relevant indicators (Figure 3.17b).

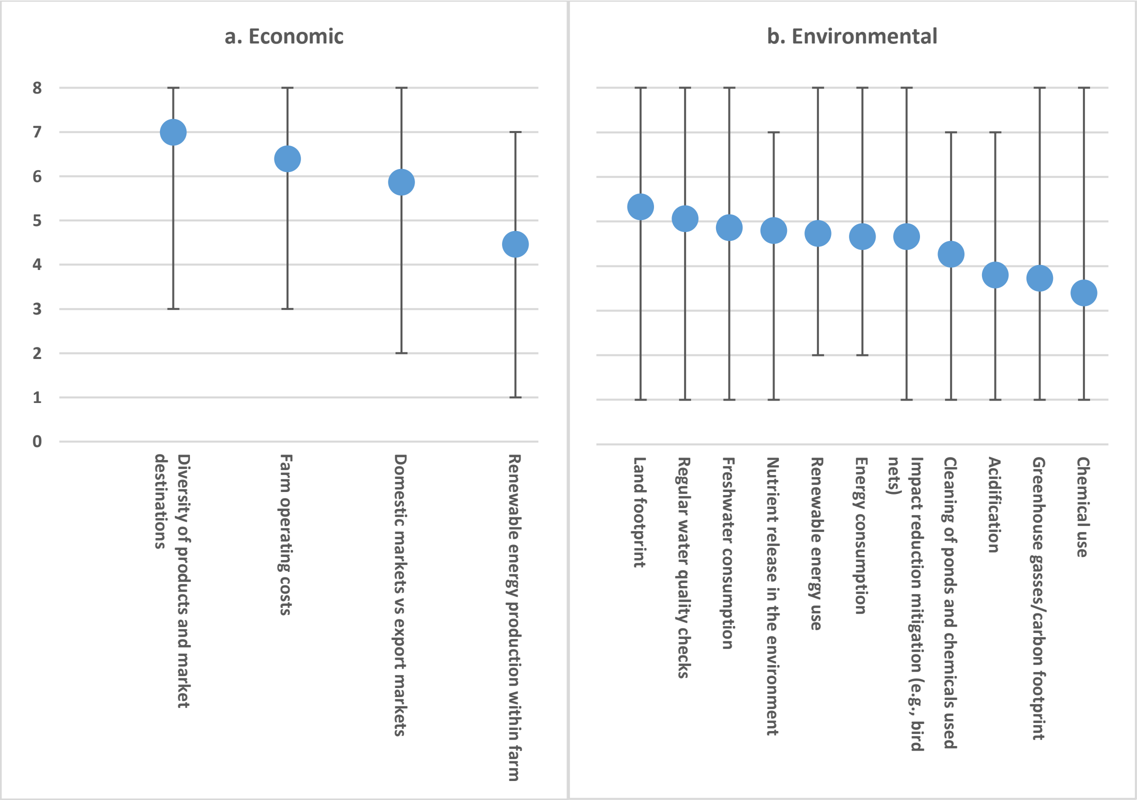


Figure 3.17a-b: Relevance scoring of the a) economic and b) environmental indicators of Polish common carp (score: 1 low importance, 8 high importance). Error bars indicate the min and max score provided by the participants (n=15).

The expert group scored “employee safety and risk reduction”, “jobs created per unit output” and “labour structure”, as the most important social sustainability indicators (Figure 3.18a). When it comes to fish welfare, “number of mortalities on the farm” and “observation of body damage” are considered the most important indicators (Figure 3.18b).

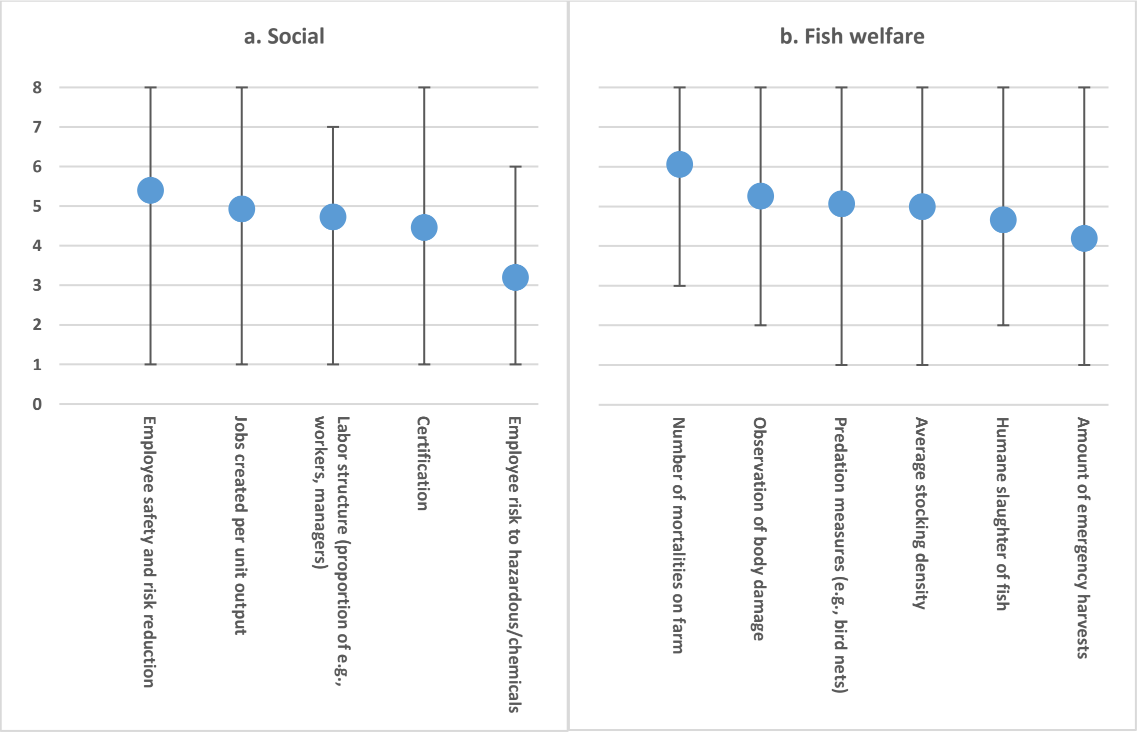


Figure 3.18a-b: Relevance scoring of the a) social and b) welfare indicators of Polish common carp (score: 1 low importance, 8 high importance). Error bars indicate the min and max score that was provided by the participants (n=15).

3.3.4.2 Delphi round 2

Industry perceptions

This section is focussing on the industry perceptions, such as general trends and sustainability. Additional it compares perceptions of industry stakeholders towards their own industry and the perceptions of the public towards their industry (Appendix A1.5 and A1.6, respectively).

Norwegian Atlantic salmon

In Delphi round one the panel of experts indicated that they perceived that EU consumers regarded Norwegian aquaculture to be more sustainable than Norwegian consumers did. These differences might be explained by the panel of experts' perceptions that EU consumers thought Norwegian water is pristine leading to the perception that Norwegian salmon was similarly of a high standard. In addition, the panel of experts also emphasised the different perceptions of sustainability (Figure 3.19).

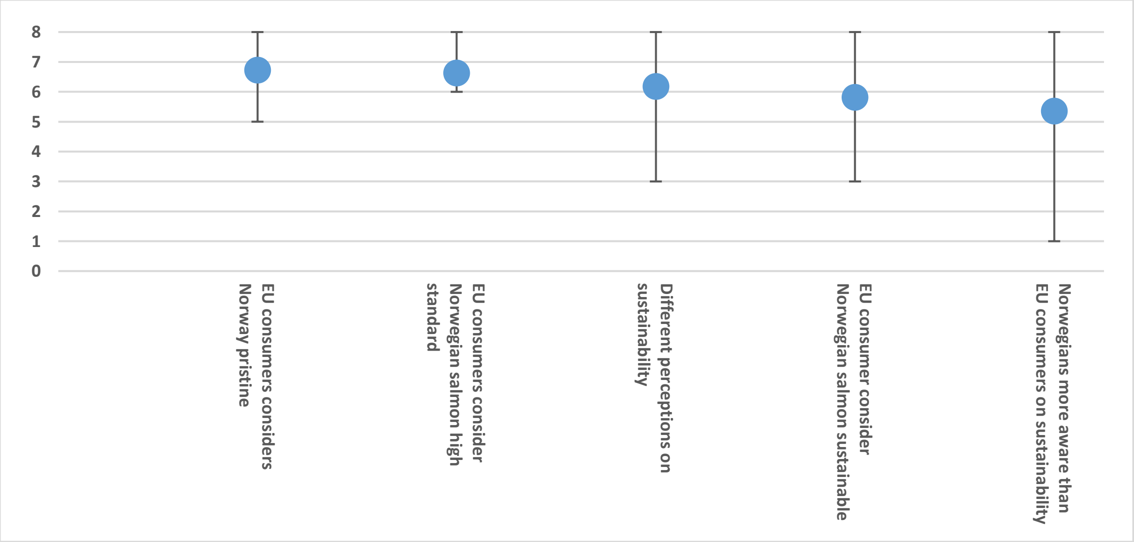


Figure 3.19: What explains the different perceptions between EU (Norwegian salmon sustainable) and Norwegians (critical towards own sustainability performance) (1 low importance, 8 high importance). Error bars indicate min-max score provided by the participants (n=11).

In Delphi round one the panel of experts indicated that novel feed ingredients are considered a key strategy to both increase profitability and sustainability. However, the panel of experts indicated that novel feed ingredient use is currently constrained by price, availability, consistency of nutritional content and quality (Figure 3.20).

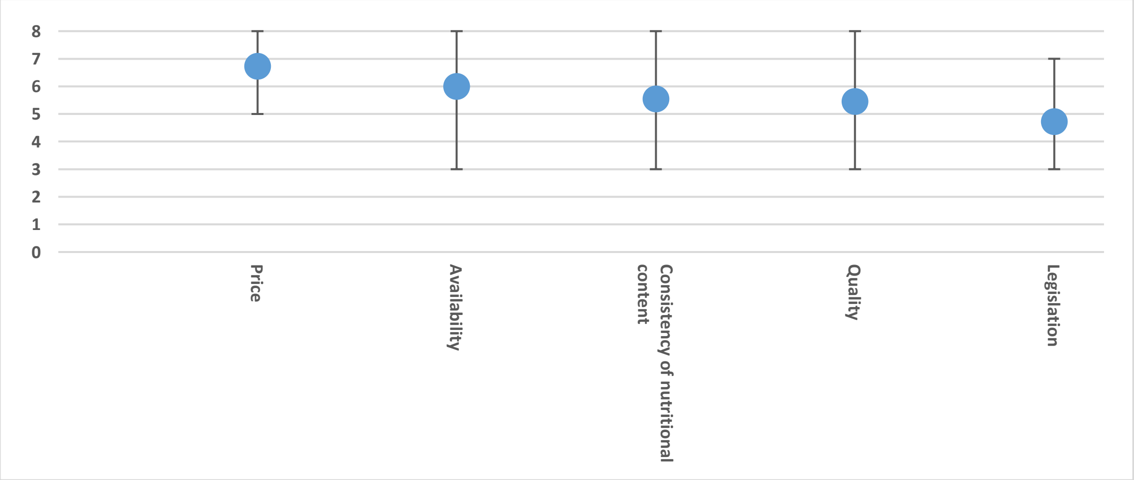


Figure 3.20: What are the main challenges of novel feed ingredients (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=11).

In Delphi round 1 I asked about environmental sustainability. In addition to sustainable feeds and technically efficient production, the panel of experts highlighted the importance of high fish welfare. In Delphi round two the panel of experts indicated that important strategies to support fish welfare are “the implementation of training in fish welfare”, which was considered most important by the hatchery/farm and veterinary/health (Figure 3.21). Additionally, “monitoring fish condition and water quality” are also considered important strategies to support fish welfare.

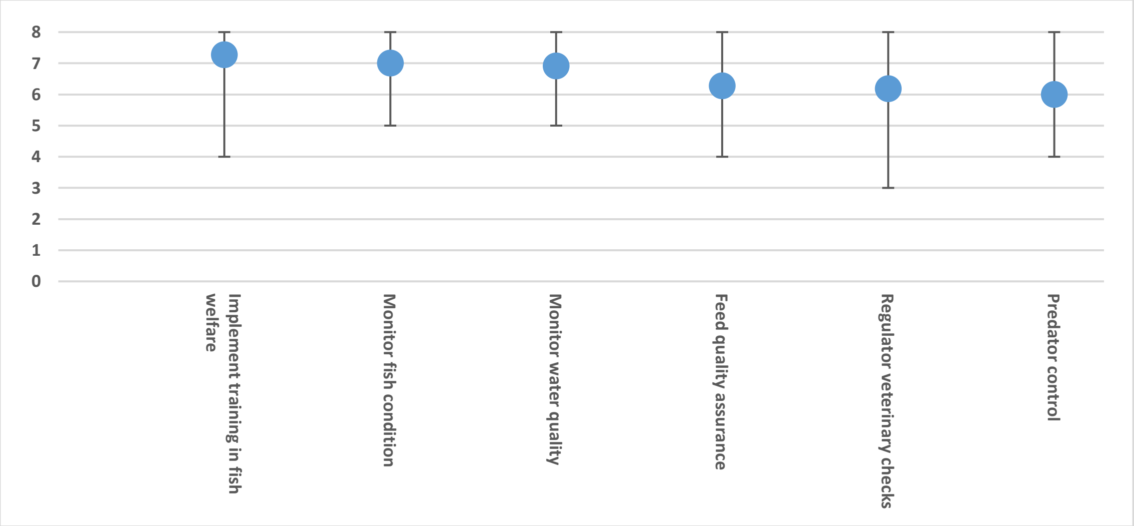


Figure 3.21: What are key strategies to support fish welfare (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=11).

In Delphi round 1 I asked about the needs to support sustainable production growth. The panel of experts showed a consensus that “government support in the form of R&D” and “collaboration between stakeholders” are needed to support sustainable intensification of the Norwegian aquaculture industry. In Delphi round 2 the panel of experts indicated that this could be in the form of “meetings to refine collective strategies” and “R&D on sustainable feeds” as the most important ones, followed up by “sharing farm performance data” and “area warning system for sea lice” (Figure 3.22).

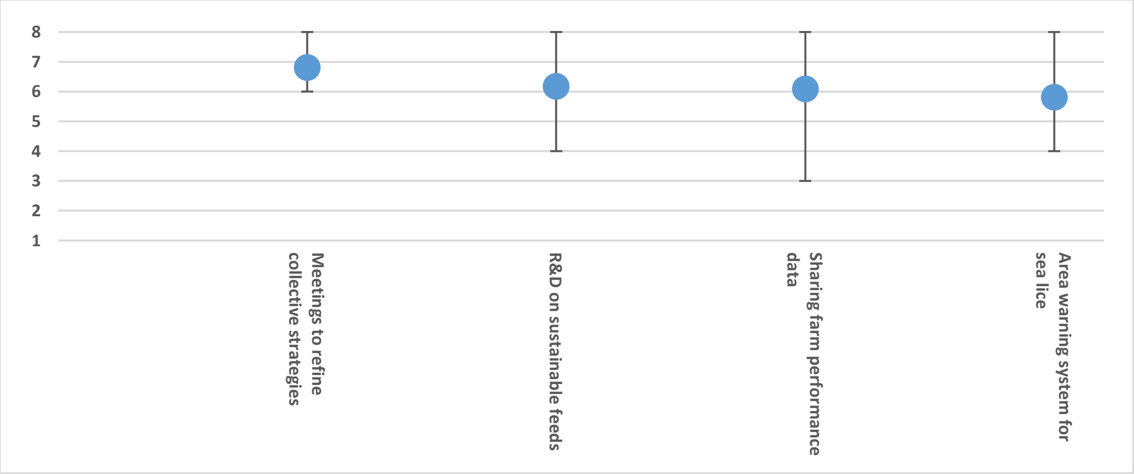


Figure 3.22: What type of collaboration is most important to support sustainable intensification (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=11).

In round 1 I asked if current EU and provincial (regional) legislation is supporting growth (production volume output) of the Norwegian aquaculture industry. The panel of experts' opinion was divided between "neither agree or disagree", "agree" and "strongly agree", while the panel of experts seem to agree that these provincial (regional) polices are supportive to become more environmentally friendly. In the second Delphi round stakeholders indicated that legislation to achieve sustainable intensification should be focussed on "maximum standing biomass regulation", "planning site selection", "financial instrument for innovations" and "legislation on environmental footprint" (Figure 3.23).

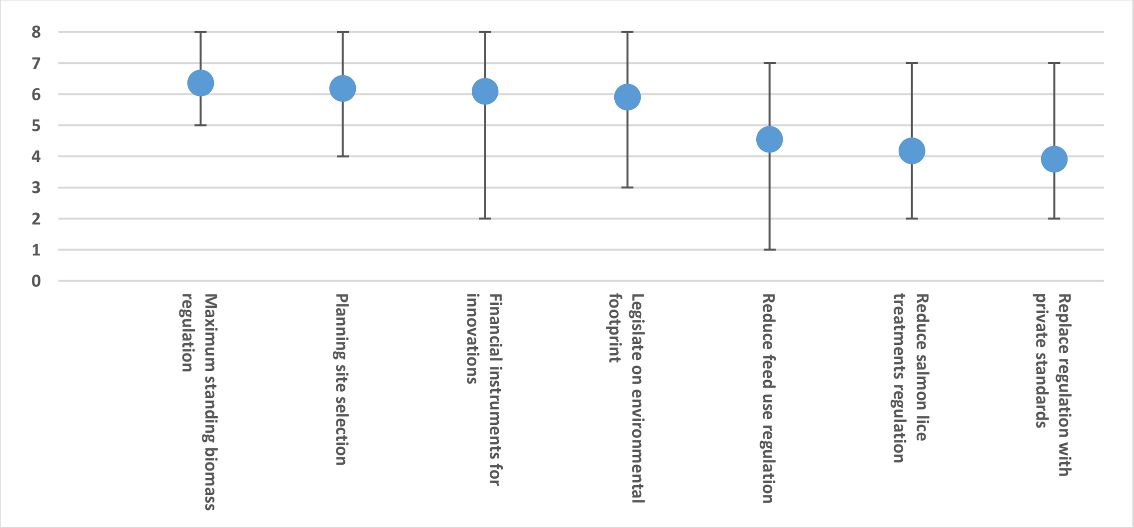


Figure 3.23: Where should legislation focus to achieve sustainable intensification (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=11).

Polish common carp

In Delphi round 1 I asked about the general trends in the carp aquaculture industry in Poland. In addition to a “steady production volumes”, the panel of experts also indicated “declining financial margins”. This could have been caused by “higher production costs” and “low carp prices due to limited season”. The panel of experts also indicated that “environmental challenges, such as the “lack of water”, also have reduced the production and profitability (Figure 3.24).

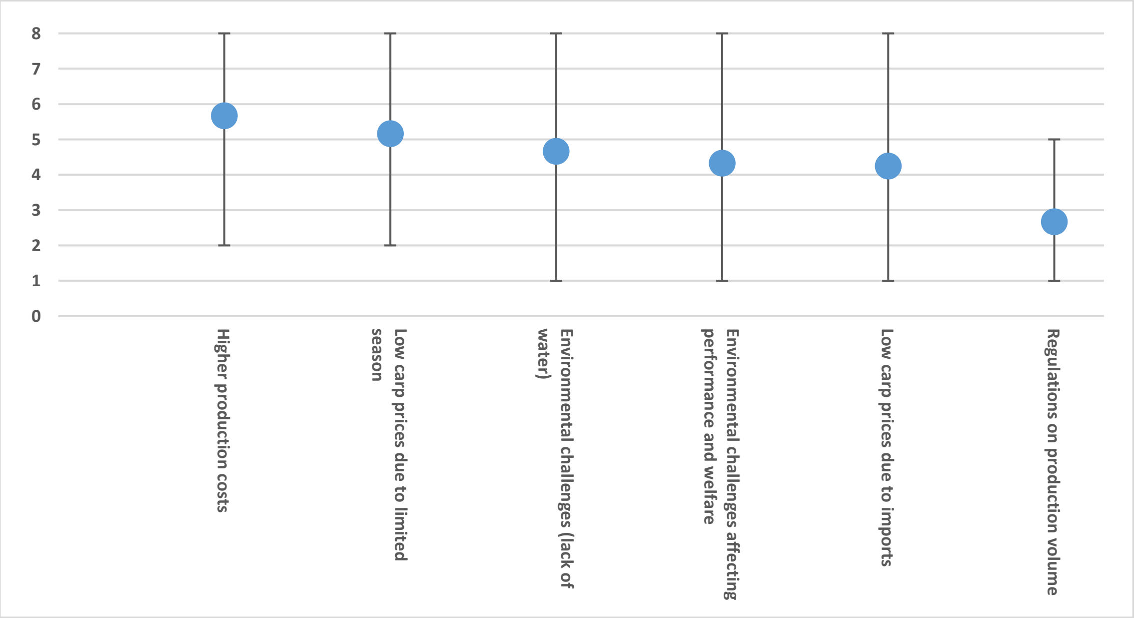


Figure 3.24: What has caused the declining financial margins for common carp in Poland (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=12).

In Delphi round one the panel of experts indicated that carp processing shows potential to increase the profitability of the Polish aquaculture industry. However, this requires a consumer perception change towards processed carp. According to the panel of experts in Delphi round two this could be achieved by “advertising differentiated products” and “promotion of natural production” referring to the low impact production characteristics, while promoting and “marketing all year consumption of carp” (Figure 3.25).

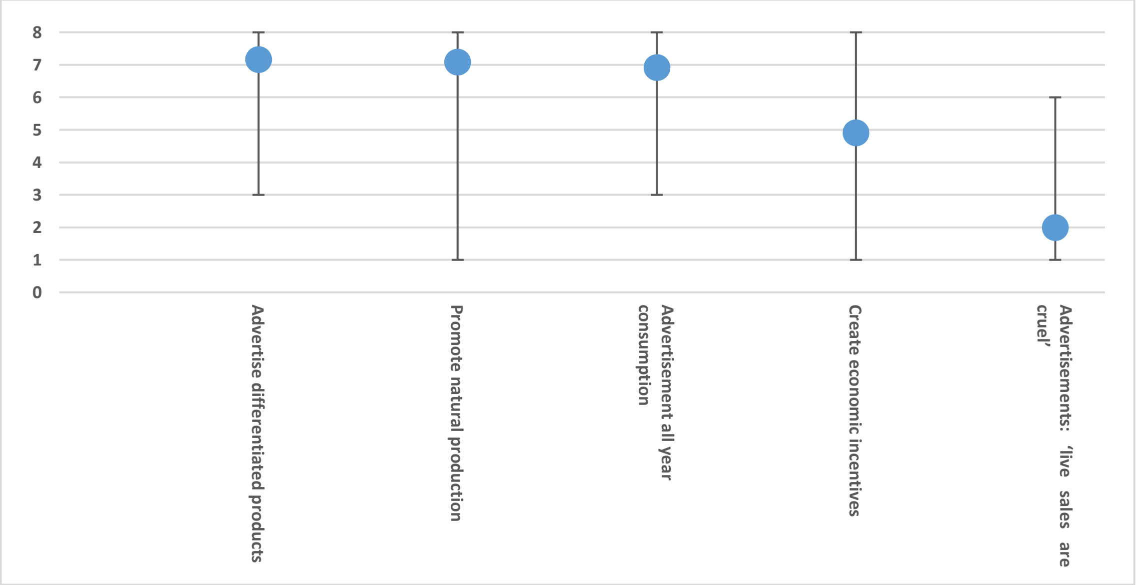


Figure 3.25: What is the best strategy to change consumer perceptions towards processed carp (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=12).

In Delphi round 1 I asked if current provincial (voivodeship) legislation is supporting the sustainable intensification of the Polish carp aquaculture industry. The panel of experts were uncertain of the perception that regional legislation is supportive for growth and environmental sustainability, indicated by mixed responses such as "not to have an opinion" and "I do not agree" on this matter. According to the panel of experts in Delphi round 2, supportive legislation (provincial/national) for sustainable carp production should have a wide focus, but high priority should be put on "financial instruments to promote carp products year-round" and "financial instruments to support small processing plants and to develop short supply chains" (Figure 3.26).

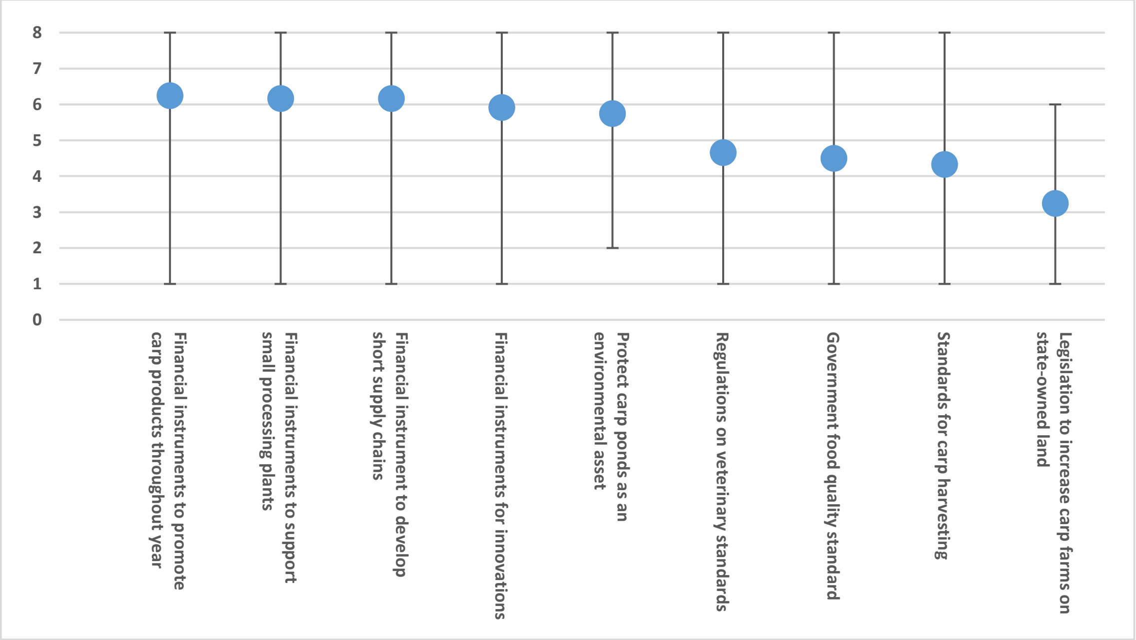


Figure 3.26: What topic should legislation (provincial/national) be focussed on to promote sustainable carp aquaculture (score: 1 low importance, 8 high importance). Error bars indicate the minimum and maximum score that was provided by the participants (n=12).

The results from the KI showed that there was a relatively weak relationship between those with most interest and those with most power, meaning change is not necessarily being directed by those with most to gain or lose. Aquaculture development could be more stakeholder-driven, according to the panel of experts if there is “support from the government + representative authorities to innovate the industry” (Figure 3.27). Additionally, “multi-stakeholder platforms and funding”, bringing together different interest groups to discuss opportunities, threats, and policy actions, could add value to a stakeholder-driven industry, while it could attract funding at the same time. Other initiatives could be to create a “government (funded) – stakeholder joint R&D initiative”.

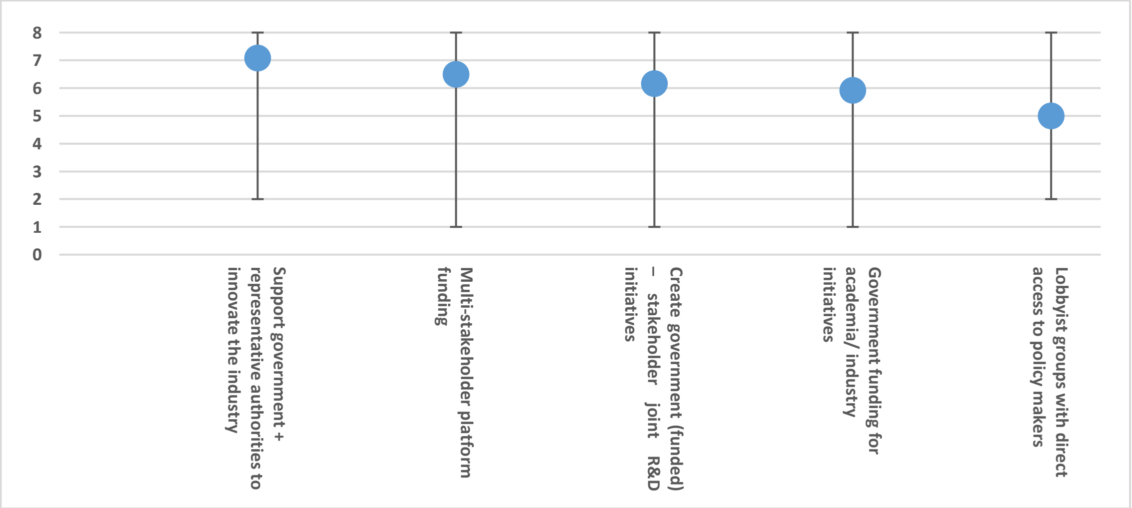


Figure 3.27: How can we make sure that aquaculture development is more stakeholders driven (score: 1 low importance, 8 high importance)? Error bars indicate the minimum and maximum score that was provided by the participants (n=12).

3.4 Discussion

The results from the initial KI surveys and Delphi panel of experts' rounds are discussed in relation to the literature, comparing the industrial scale Norwegian Atlantic salmon farming with extensive and traditional Polish common carp farming. I will briefly explore the industry characteristics and discussing the key results from KI surveys and the Delphi panel of experts' survey in relation to the stakeholders, innovation, sustainability, and legislation.

Norway is the largest EEA aquaculture producer and production increased from approx. 440,061 MT in 2000 to 1.62 million MT in 2021 (Figure 1.2). Nevertheless, certain industry segments show a widespread environmental and socio-economic concern in relation to the industry proposed expansion, especially in the North of Norway there seems to be a strong division on the social acceptability of the industry (Bailey and Eggereide, 2020). This might explain the Delphi findings indicating a "neither agree nor disagree" response when asked to the Norwegian panel of experts if they perceive the industry to be sustainable. Conversely, the same panel of experts indicated that their industry is perceived as sustainable by the public in Europe. Nevertheless, despite the optimism, the panel of experts indicated ongoing challenges and concerns around sea lice infection, and production limits for farmers imposed by the government.

Stakeholders as part of the KI surveys indicated increased sustainability concerns around the use of certain feed ingredients, such as FM and FO, but also about their substitutes, such as plant ingredients. This was also confirmed by the panel of experts in the Delphi survey, showing a clear consensus around the low potential of plant ingredients to improve environmental sustainability, feed efficiency, fish welfare and public consumer perceptions. The substitution of marine ingredients by plant ingredients, or where one biotic resource is replaced by another, as observed in the Norwegian salmon industry, is considered a weak sustainability principle (Hansen, 2019; Luthman *et al.*, 2022), which is associated with trade-offs. Certain plant ingredients could have a negative effect on the nutritional value of the final product, could result in poor fish health and are associated with a negative environmental performance of the diet (Malcorps *et al.*, 2019a; Newton and Little, 2018; Sprague, Dick and Tocher, 2016; Torrissen *et al.*, 2011). Even sustainable certified soy production could have (social) sustainability implications, as they have not sucessfully protected the access of local communities to land and water in Brazil, according to a study by Schilling-Vacaflor (2021). Nevertheless, the Norwegian KIs showed interest in a range of novel feed ingredients (micro-, macroalgae, insects, fish by-products, single cell proteins) and the Norwegian panel of experts showed interest in sustainable intensification and considered novel feed ingredients, technically efficient production (e.g., resource efficiency, connecting farms to main electricity net, less energy use) and high fish welfare key aspects of the environmental sustainability of the industry. They emphasize that novel feed ingredients could reduce environmental impact, feed efficiency, increase profitability, benefit fish welfare, and improve public consumer perception. More specifically, “marine ingredients from fishery processing by-products” and “microalgae” showed the highest preference to improve feed efficiency, fish welfare and public perception, while insect protein and seaweed are also listed in the top three to support sustainability, feed efficiency, fish welfare and improve the public perception towards farmed fish.

When it comes to by-products, the “circular economy/recycling” and “novel feed ingredients” in combination with a focus on “quality rather than quantity” are considered appropriate strategies to increase the profitability of the salmon industry, according to the panel of experts. I assume the nutritional potential of “marine ingredients from fishery processing by-products” is equally applicable to marine ingredients from aquaculture processing by-products, as the literature indicates that it could support the food, feed and industrial output of the aquaculture industry without using more resources (Stevens *et al.*, 2018; Malcorps *et al.*, 2021c). This is a key example of sustainable intensification of the industry, producing more from the same resources, while staying within production limits imposed by the government.

The regulations regarding production limits were considered a negative and uncertain sustainability factor by the Norwegian stakeholders. The use of marine ingredients from by-products in combination with novel feed ingredients such as micro-algae could contribute positively to health and welfare of fish, according to Hua *et al.* (2019). However, the use of “marine ingredients from aquaculture processing by-products” was never explicitly asked during the KI and Delphi survey due to an EU regulation (No 1069/2009). This regulation prohibits the feeding of farmed fish with processed animal protein derived from farmed fish of the same species, also called intraspecies feeding (EC, 2009). While this is only applicable to animal protein (not oils), by-products can still be used as feed for other species. It is important to highlight that this rule has a major impact on the utilisation potential of Atlantic salmon by-products in feeds in Norway due to the dominance presence of the Atlantic salmon sector. Therefore, these by-products are exported to foreign markets where they can be used in aquafeed or livestock feed. Nevertheless, this might explain (partly) the panel of experts’ uncertainty around EU legislation supporting the growth (production volume output), while it showed a consensus in terms of EU legislation supporting the aquaculture industry to become more environmentally friendly.

Feed production is the most significant source of global environmental impact of fed aquaculture production (Bohnes *et al.*, 2018) and the KI and the panel of experts indicating potential of novel feed ingredients to improve the sustainability of the salmon industry. Nevertheless, the panel of experts also acknowledged that the use of novel feed ingredients is constrained by availability and price (main concerns according to the three feed experts), consistency of nutritional content, and quality, which are identified as the most important challenges for novel feed ingredients, which is in line with the literature (Pelletier *et al.*, 2018; Hua *et al.*, 2019). The KIs also indicated uncertainty around feed ingredients by including (novel) feed ingredients in both the positive, uncertain, as well as the negative sustainability factors. While some of this uncertainty has to do with the availability, price, and quality of novel feed ingredients, results also suggest uncertainties around the environmental performance. This is also in line with the literature, which showed dissapointing environmental performance of microalgal ingredients (Maiolo *et al.*, 2020b), cyanobacteria (Smetana *et al.*, 2017), and insect meals (Quang Tran, Van Doan and Stejskal, 2021; Smetana, Schmitt and Mathys, 2019). While some (e.g., insect meals) of these ingredients showed an environmental impact profile lower than many existing protein sources, the production methods of these ingredients can be further developed to make it more sustainable, using LCA to identify hotspots and room for improvements. In regards to the use of insects as feed ingredients, legislation is considered a bottleneck in terms of efficiency and sustainability. The EU regulation 2017/893 defines insects as farmed animals and states that allowable feed substrates must be of feed-grade (EC, 2017). Consequently, insects cannot be fed “waste“, such as former foodstuff, fish or food losses and other feed materials not meeting the regulations (Gasco *et al.*, 2020). This means that circular economy principles cannot be applied comprehensively to feed insects, and that some of the allowable subtrates might be more (cost) efficiently fed directly to fish or other animals in terms of feed conversion ratio. This might explain why “insects protein“ is mentioned third after “marine ingredients from fishery processing by-products” and “microalgae”, when the panel of experts was asked about the potential of these novel feed ingredients to improve feed efficiency of the salmon diet.

The overal sustainability goals and importance of the sustainability indicators might differ within each value chain depending on the stakeholders surveyed, while the most important indicators per category (socio-economic, environmental and welfare) could differ significantly between the Norwegian Atlantic salmon and Polish common carp value chains. It is important to have a broader look at sustainability, beyond the narrow framing of seafood sustainability in terms of fisheries management (for feed) and ocean health. A narrative beyond ocean health is important to include aquaculture into the discussion on global food system sustainability, according to Tlusty *et al.* (2019). In terms of economic sustainability indicators, the Norwegian panel of experts showed an consensus on “feed efficiency“ and “fish mortality at farm“ as their most important economic indicators, while the Polish panel of experts indicated a “diversity of products and market destination“, as well as “farm operating costs“ as most important. This can easily be explained by the high relative operating costs (up to 50%) of feed use at the salmon farms (Jakobsen, Berge and Aarset, 2003; Hansen, 2019), while the production of common carp in Poland requires barely any commercial feed input due its natural production characteristics (Raftowicz and Le Gallic, 2019).

In terms of the environmental sustainability indicators, the Norwegian panel of experts highly value the “recycling of by-products in other industries”, “feed efficiency“, “carbon footprint“ and “nutrient release in the environment“. They are clearly focussed on efficiency, resources used and its impact on the environment. This might be explained by the need for comprehensive sustainability indicators to compare different aquaculture systems. While intensive systems could be much more sustainable compared to extensive systems, this can only be determined based on the capacity of production to counterbalance the resources used and pollutants produced according to Valenti *et al.* (2018). The Polish panel of experts had a different view and find “land footprint“ and “regular water quality checks“ most important. This could be explained by reasons mentioned before in relation to the extensive nature of Polish common carp aquaculture (Raftowicz and Le Gallic, 2019), and low commercial feed (mostly grain as fish feed) input, therefore the absence of these feed related indicators as seen for Norwegian Atlantic salmon. The selection of “land footprint“ might be explained by the low allowable stocking densities of the earthen ponds, as a result of a regulation allowing fish growth to a ceiling of 1,500 kg ha^{-1} year^{-1}, as part of the water law “*Ustawa z dnia 20 lipca 2017 r. - Prawo wodne, (consolidated text Dz.U. 2017, item. 1566) (KancelariaSejmu, 2017).* Consequently, as stocking densities function as a bottleneck for growth, the “land footprint” is an indicator of the maximum yearly fish growth capacity of a farm.

The panel of experts mentioning of “regular water quality checks” could be traced back to concerns around water sources (precipitation or surface water), which is affected by climate change as mentioned by the KIs and panel of experts and in line with the literature of Lasner (2020). In terms of social sustainability indicators, Polish and Norwegian stakeholders seem to agree, both valuing “employee safety and risk reduction” as most important, followed by “risk exposure to hazardous/chemicals“ for the Norwegians, while the Polish seem to value “jobs created per unit output“ as most important. According to Valenti *et al.* (2018), social sustainability indicators should reflect benefits to local communities. In the case of the Atlantic salmon industry, benefits are geographically dispersed, from e.g., farm employment in Norway to outsourced secondary processing in Poland.

In terms of welfare sustainability indicators, the Norwegian panel of experts valued “fish welfare training for employees” and “health management plan”, while the Polish panel of experts prioritised the “number of mortalities on the farm“ and “observation of body damage“ as most important. The Norwegians have a focus on training and management, while the Polish clearly focus on direct welfare issues such as mortalities and the observation of fish welfare. This is also reflected in the KI survey results showing high interest in the use of big data for management and fish welfare, while this was not of interest for most stakeholders in the Polish common carp value chain. The different perceptions might be explained by the industrial versus traditional and extensive scale of production (Raftowicz and Le Gallic, 2019; Asche, Cojocaru and Roth, 2018).

Sustainable intensification support of the Norwegian Atlantic salmon industry in the form of collaborative effort, such as “government support (R&D)” and “collaboration between stakeholders” are considered most promising according to the panel of experts. This seems to match with the KI survey results, showing power and interest results, indicating that the industry is stakeholder led and that the stakeholders are keen to innovate, which makes the implementation of new innovations easier. More specifically, the panel of experts emphasised the high potential of circular economy principles to support sustainable intensification, while at the same time vertically integrated companies and stakeholders active in fish processing showed medium to high power and interest to implement such industry changes. This is in line with the findings of Asche *et al.* (2018), showing that Atlantic salmon follows the same development path as the chicken industry with a strong focus on efficiency and reducing time between production and delivery to customers. Effective processing is important to increase shelf life and quality of the end products, which in return creates value. Norway is an example where full processing takes place and most aquaculture processing by-products are utilised, but there is still potential to increase volumes and value addition, according to Olafsen (2014). The characteristics of the Atlantic salmon industry, such as adopting technologies, knowledge and processes from other food producing industries, the increase in production and vertical integration has improved increased competitiveness leading to industry growth (Asche, Cojocaru and Roth, 2018). This is exactly the opposite of the more traditional Polish common carp industry, which shows barely any signs of intensification, such as novel feed ingredients, fish processing and vertical integration as indicated by the KI and panel of experts. Nevertheless, while traditionally most carp demand is domestically around the Christmas period resulting in a large volume (up to 80-90%) of live common carp on the Polish market (Raftowicz and Le Gallic, 2019; Raftowicz *et al.*, 2020), respondents have indicated that a diversification of carp products could increase the year around appeal for carp. Nevertheless, the Polish KIs showed a general lack of motivation for innovation of the stakeholders involved. The Polish power/interest grid (Figure 3.5) showed low rising power in relation to rising interest, indicating that this value chain is not stakeholder driven and that there is a lower appetite for change compared to the Norwegian value chain.

Intensification in processing and the utilisation of fish by-products requires collaboration and collective action, which is challenging due to the dispersed power and interest (in innovation) of the different stakeholders. Conversely, the Polish KIs and panel of experts emphasised the potential of carp processing and strategic utilisation to support the sustainable intensification of the industry. While the overall KI group showed a lack of power or motivation for innovation, carp processors showed a relatively high interest in innovation, but a relatively low power to implement it. Interestingly, retailers and NGOs (environmental and ethical groups) showed high power and high interest to make industry changes, which could possibly match with the current trend of moving away from consuming live carp and diversifying products at retailer level, because of negative messaging from NGOs and media as indicated by the KI and panel of experts. Nevertheless, this new area brings uncertainties for farmers, producers and retailers and the industry. The results indicate that most stakeholder actors agree on the general trend of steady production volumes but declining financial margins. However, the Polish expert group also showed a consensus that EU legislation could support growth and environmental sustainability of the industry. More specifically, increased processing, support, and investments to promote carp consumption throughout the year, diversifying carp products promoted through marketing and advertising campaigns and events. However, according to personal communication with Lasner (2021), from an economic point of view, most of the measures proposed to the panel of experts involve a regulated market and a massive engagement of the state into the carp economy. He emphasised that the state cannot create a demand or give carp farmers a processing plant. However, public engagement, in particular where a public interest occurs and contradicts economic objectives is important and needed, such as in the case where climate change impact mitigation is needed by internalising costs of emissions of economic value chains. In this case, funding programmes for entrepreneurs could support innovation and transition to processed carp. He referred to the SUCCESS project, which highlighted the importance of integrating carp (biology, history, and processing) in the schedules of public schools, finding a synergy between tourism and the common carp aquaculture industry by promoting its cultural, economic, and environmental value for the region and by offering carp dishes in local restaurants.

KIs and panel of experts' indicated that diversification of activities at the farm, such as tourism could also be an appropriate strategy to increase profitability of the industry, which has been confirmed by findings in the study of Raftowicz *et al.* (2019), and therefore making it less reliant on subsidies. While the Polish common carp industry is already transitioning towards diversification, similar strategies to those occurring in the German carp-growing region (Aischgrund region) could be adopted, such as establishing carp tourism alongside broader (outdoor) tourism activities, by setting up tourist shops and training local carp farmers to show tourists around, bus excursions and organized visits to the local carp museum. This includes also promotion material online on social media platforms to create awareness (Gallic *et al.*, 2018). This could increase the appetite for carp products in combination with new product forms and sustainability certification to highlight the natural characteristics of carp farming (Feucht and Zander, 2018). This study highlights potential for new carp products in Germany and Poland by identifying new product forms (e.g., bone cut carp fillet), increase availability, avoiding off-flavours and the provision of (new) recipes as carp is considered difficult to prepare by some (Zander and Feucht, 2020). This is in line with the panel of experts' responses, where most stakeholders seem to agree that carp processing could increase profitability, especially when it comes to processing into fillets, while they also indicate that increased processing could also improve the image of carp farming. In line with the natural production characteristics of carp, an initiative by the European Commission called the "Action Plan for the Development of Organic Production" aims to boost the production and consumption of organic products in Europe and to significantly increase organic aquaculture output in the union (TheFishSite, 2021). All the strategies combined might increase the demand for the more traditional and naturally produced carp, especially regarding the consumer segment that shows willingness to pay more for sustainable/organically produced products and product labels, as long as it can meet quality criteria such as taste and convenience (ready to cook). A study from Raftowicz (2020) surveying consumers located a short distance from the largest complex of carp fishponds in Poland, indicated that price was not a factor in determining the purchasing behaviour of consumers in Poland's carp market, but tastes and preferences, such as a demand in a certain season, played a much greater role. The study concluded that a focus on enhancing consumers' perception of carp as a healthy and high-quality should be the main priority.

The Polish panel of experts highlighted that within Poland, the Polish carp aquaculture industry is perceived as sustainable, while they mention "not to have an opinion" in terms of Polish carp aquaculture being perceived sustainable by the public in Europe. This might be explained by the lack of general knowledge of aquaculture and therefore understanding of foreign markets and consumer perception towards their products. Nevertheless, the Polish stakeholders showed more optimism towards their own industry regarding the extensive production characteristics in harmony with nature, which is also confirmed by Raftowicz and Le Gallic (2019). These practices enables the ponds to function as ecosystem services, while it also contributes to cultural value and the region's identity (Lasner *et al.,* 2020). While provincial and national legislation was not considered supportive in terms of the sustainable intensification of the industry, the Polish panel of experts providing a relatively high importance score to "protect carp ponds as an environmental asset" when asked what topic legislation (provincial/national) should be focus on to promote sustainable aquaculture. This is in line with the positive sustainability perceptions mentioned by the KIs, such as "EU funds for innovation/diversification", which also refers to the environmental subsidies in relation to stocking densities as mentioned in the beginning of this paragraph. In addition, the "extensive production characteristics" and "slow food (in balance with nature)" and "low energy use and waste", was also mentioned referring to the ecosystem services provided by common carp aquaculture in Poland. At the same time, the panel of experts also mentioned that diversification activities at the farm (tourism and farming of other species) are identified by the panel of experts as the most profitable strategy to increase profitability of the industry. Overall, this really indicates the importance of the traditional and extensive characteristics providing ecosystems services to nature and society. According to Siuta & Nedelciu (2016), the conservation and restoration of wetlands also has a significant socio-economic benefit in terms of its ecosystems services, as well as direct environmental benefits for its intrinsic value, biodiversity preservation and to combat climate change.

Most farms are in Southern Poland, and were constructed between eleventh and seventeenth century, which is considered the Golden Era of Polish carp farming. In this time huge ponds were constructed ranging from 100 ha up to 1000 ha and many still exists today, especially in the South-Western part of Poland, the Barycz Valley (Raftowicz and Le Gallic, 2019). The river Barycz fulfils an important role as the main water supply, supporting continued production for over 800 years and it is considered is the largest carp breeding centre in Europe and the largest nature reserve in Poland (Lasner *et al.*, 2020). However, concerns around water were mentioned by the KIs, such as "climate change (relation to water availability)" and "lack of water to fill up ponds" as the most important negative sustainability perceptions. Water availability in the future is uncertain and shortages are expected

(Lasner *et al.*, 2020), partly influenced by climate change and thus production of common carp may be subjected to rapid and unpredictable changes with unknown outcomes. Especially, because water resources in Poland are already under pressure, as Poland is classified as a country with low water resources, and the country has experienced meteorological droughts over the last years (Kubiak-Wójcicka and Machula, 2020; Kubiak-Wójcicka and Bak, 2018). Additionally, droughts and consequently the reduction in flow of rivers and streams could possibly increase the concentration of harmful pollutants, as observed in other river systems (Vliet and Zwolsman, 2008; Mosley *et al.*, 2012; Hübner and Schwandt, 2018). While Poland and its fish farms are affected by relatively low water resources and the effects of climate change, measures in relation to water retention in the catchment area are recommended. Included in these recommendations are retention reservoirs and the slowing down of water outflow (Michalczyk and Sposób, 2021). Based on these recommendations it seems that common carp ponds are not only affected by a lack of water availability, but they could also be part of the solution, addressing the negative sustainability concerns of the KIs. This is also in line with the panel of experts' recommendation on suitable mitigation strategies against the effects of climate change, such as "more efficient use of water resources" and "engineering solutions (e.g., water channels)".

When it comes to the use of big data for management, support, and fish welfare, it is no surprise to observe the low interest from the Polish KIs due to its extensive and traditional characteristics. There is barely any interest to invest in big data capabilities, as most carp farms in Poland are barely profitable and the economic situation is difficult (Turkowski and Lirski, 2010; Lasner *et al.*, 2020), consequently affecting the ability of farmer to adapt or diversify their activities (Lasner *et al.*, 2020). Conversely, Norwegian KIs showed a high interest in big data for management, support, and fish welfare as a result of the intensive and industrial characterisation of the Atlantic salmon aquaculture industry. Collecting data through interconnected farm sensors provides decision support for farming operations through analysing, monitoring and interpretation of big data in a cloud ecosystem, which is also defined as "precision aquaculture" (O'Donncha and Grant, 2019). While this enables the farmer to have a better control over the production process and its efficiency, it could also benefit fish welfare by observing fish behaviour and making the necessary adjustments to inputs (e.g., feed input) or the environment (dissolved oxygen) where possible (O'Donncha *et al.*, 2021). In recent decades innovation and productivity growth are the main sources for the establishment of the successful aquaculture industry in Norway. In line with this trend, the industry is profitable and at scale with many vertically integrated companies (Asche *et al.*, 2013; Asche, Sikveland and Zhang, 2018). A high power and interest to innovate is observed (Figure 3.4), overall indicating capacity to invest in big data technologies.

3.5 Conclusion

The definition of "sustainable" differs between the more traditional Polish common carp and industrialised Norwegian Atlantic salmon industry, which is also observed in the differences in their perceptions towards sustainable intensification strategies. Increasing consumer demand for ecolabels and environmental-friendly production practices, especially in the Global North are rewarded with price premiums (Barclay and Miller, 2018; Tlusty, 2012; Ward and Phillips, 2008), which could be an opportunity for the traditional Polish common carp sector to increase demand, while also obtaining a higher price, improving the profitability of the industry as well. Especially, because the Polish common carp industry showed a low appetite for change and seemed to prioritise the preservation of traditional, natural, and low impact carp farming in harmony with nature.

Certification contributes to the establishment of environmental and social industry standards, but is also limited and should therefore be considered as only part of the sustainable aquaculture toolkit (Bush *et al.*, 2013). Continuous improvements are crucial considering the fact that sustainability is a journey and not an endpoint (Tlusty and Thorsen, 2017). The Norwegian Atlantic salmon industry dominates the EEA aquaculture species portfolio, and most stakeholders showed a high appetite for innovation. More specifically, the processing industry has resources and interest to implement circular economy principles in the form of increased processing and strategic utilisation. Similar interest is also shown towards novel feed ingredients to improve the sustainability performance, but availability, price, quality, and environmental performance remains a challenge. This clearly indicates an overall focus on resource efficiency, showing that Atlantic salmon follows a similar development path as the chicken industry, as shown by Asche *et al.* (2018). The adoption of knowledge and technology could enhance resource efficiency significantly and improve the environmental sustainability, while also increasing the competitiveness. Big data could increase resource efficiency, highlighting (un)sustainable production practices, increasing transparency and traceability of the final product, while also addressing disease outbreaks and fish welfare concerns. This would enable the EEA aquaculture industry to produce more competitive products, while reducing its environmental footprint, providing nutritious seafood to its population.

CHAPTER 4: BY-PRODUCTS AND THE CIRCULAR ECONOMY

4.1 Introduction

The European (EU-28) seafood and aquaculture trade with third countries (imports and exports) ranked second largest after China in 2019 (EUMOFA, 2020b). Domestic European (EU-27) seafood consumption in 2019 account for 23.86 kg capita^{-1} year^{-1}. However, consumption was highly variable, with Portugal (57.19 kg capita^{-1} year^{-1}) at the higher end and Hungary (6.34 kg capita^{-1} year^{-1}) at the lower end in 2019 (FAOSTAT, 2023). The EU Live Weight Equivalent (LWE) seafood supply of 12.89 million Metric Tonnes (MT) in 2020 originated from domestic capture fisheries (23%) and aquaculture production (9%) in 2020, with the rest of the balance supplied by imports from non-EU member states derived from capture fisheries (52%) and aquaculture (16%) (Figure 1.1). Norway, as part of the European Economic Area (EEA) member, fulfils an important role, supplying 25% of total seafood imports into the EU, mainly farmed Atlantic salmon, which represents 35% of the total estimated consumption of aquaculture products and 15% by volume of all fish and seafood products imported (EUMOFA, 2019a). However, supply could be increased by more efficient processing and strategic value addition. Currently, processing by-products from both wild capture and aquaculture are "underutilised" in Europe as a whole (Jackson and Newton, 2016). Such under-utilisation can occur either when quantities of by-products are limited such as when fish are marketed whole or when markets for segregated by-products are undeveloped. Consequently, this results in the accumulation and discard of by-products at the processor or household level, highlighting an opportunity to increase production, while enhancing sustainability. These limitations have been acknowledged as an action point under the forthcoming EU "Farm-to-Fork Strategy" (EC, 2008; EC, 2020b) and being a key element of sustainable development goal (SDG) 12, "*ensuring sustainable consumption and production patterns*" (UNDP, 2020).

Omega-3 (n-3) long-chain polyunsaturated fatty acids (LC-PUFA), eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are key micronutrients for human and animal health (Tocher *et al.*, 2019; Hamilton *et al.*, 2020). Additionally, seafood consumption can improve intake of other key micronutrients such as vitamin D and B12, iodine, selenium and other minerals (Aakre *et al.*, 2019), as well as being a good source of bioavailable protein. An estimated one third of all EPA+DHA originating from wild and farmed fish globally is discarded (Hamilton *et al.*, 2020). A global shortage and increase in value of these nutrients creates incentives to use by-products more efficiently.

Increasing demand for low environmental impact feed ingredients for Europe's livestock and aquaculture sectors has become a major driver for more efficient strategies to use processing by-products within a circular economy. European aquaculture production is highly dependent on imported feed ingredients from both marine and terrestrial systems, such as FM, FO and soy (Newton and Little, 2018), which expose the sector to external economic shocks (Troell *et al.*, 2014) and criticisms of "off-shoring" environmental impacts associated with their production. Feed production is the most significant source of environmental impact of fed aquaculture production (Bohnes *et al.*, 2018). A continued dependence on fish meal and oil for the marine carnivorous species mainly farmed in Europe (Naylor *et al.*, 2021) has led to sustainability concerns remaining focused on the use of marine ingredients in the context of "ocean health" (Tlusty *et al.*, 2019) despite longstanding efforts to substitute them with alternative ingredients (Naylor *et al.*, 2009; Froehlich *et al.*, 2018). Such transformations, demonstrated most obviously by the high levels of soy products now fed to salmon (Newton and Little, 2018), have their own challenges, not least of which has been a shift in sustainability concerns from the oceans to sensitive terrestrial ecosystems (Newton and Little, 2018; Malcorps *et al.*, 2019a). Moreover, the substitution of marine ingredients with plant ingredients in aquafeeds risks both compromising the health and welfare of the cultured animal (Rana, Siriwardena and Hasan, 2009; Saito *et al.*, 2020) and can also affect micro- and macro nutrient levels in the final consumed product (Sprague, Dick and Tocher, 2016; Nichols *et al.*, 2014; Saito *et al.*, 2020). A "food system approach" is crucial to avoid problem shifting by better understanding the sustainability (socio-economic and environmental) trade-offs of a transformation (Cook *et al.,* 2015), as unintended consequences of shifts in feed type used may occur along the entire value chain. A re-evaluation of the potential to increase the supply of marine ingredients from under-utilised by-product resources has received far less attention.

A comprehensive analysis of the available volumes and nutritional value of by-products from the main aquaculture species in Europe remains largely undocumented. Norway is an example where full processing takes place and most aquaculture processing by-products are utilised, but there is still potential to increase volumes and value addition (Olafsen *et al.*, 2014). However, elsewhere mixing by-products is still a common practice, with more directed to animal nutrition rather than direct to humans (Stevens *et al.*, 2018). The absence of strategical sorting and grading of fish by-products can dilute overall nutritional value and limit potential application. Stevens *et al.* (2018) showed that better by-product separation offered opportunities for value addition in farmed salmon in Scotland. Therefore, the main aim of this chapter is to characterise the available volumes and nutritional content, and discuss potential industrial applications, of the different by-products derived from the major farmed species in Europe. Additionally, the stakeholders from the common carp sector in Poland (CH3) identified opportunities to move away from live carp sales and other traditional product forms and develop the primary and secondary processing sector. The potential to increase the economic value of the industry is briefly explored in a carp processing model, which is using collected primary and secondary data on product form and price (4.2.3 and 4.3.3).

4.2 Methods

4.2.1 Identifying by-product volumes in Europe

The methods underpinning the by-product balance fall into two sections. First, data on European aquaculture production and trade was obtained from the FAO (2020c). Production volumes for the European key species was adjusted for trade in processed commodities which allowed by-product volumes to be estimated in each country. Data provided by IIM-CSIC from pilot scale work on hydrolysate, peptones and gelatines was used to determine potential volumes of these products from the available by-product quantities.

By-product fractions and commodity conversion factors

The FAO provides a list of standardised conversion factors (Table 4.1) for different commodities (FAO, 2022a). However, these conversion factors are averaged and not always species specific. For this analysis I calculated species specific conversion factors based on a published lab analysis by Malcorps *et al.* (2021c), available in section 4.3.2 in table 4.12, and compared these values with the FAO commodity factors to verify the results. The conversion factor to the initial LWE volume for each species is calculated as follows; 100/(100 - % of each by-product).

Table 4.1: Seafood commodity conversion factors (CF) based on FAO data (2022a) and compared with data from a lab analysis by Malcorps et al. (2021c).

FAO commodity groups (FAO, 2022a)	**Conversion factor (CF) based on Malcorps *et al.* (2021c)**							**CF (FAO, 2022a)**
Conversion factor (CF) group for seafood commodities	**Form**	**Atlantic salmon**	**Rainbow Trout**	**European seabass**	**Gilthead seabream**	**Common carp**	**Turbot**	
Frozen – whole	Whole	1	1	1	1	1	1	1
Dressed - gutted, head on (HOG)	Viscera removed	1.12	1.12	1.09	1.08	1.16	1.06	1.13
Dressed – gutted, head off	Head + viscera removed	1.26	1.26	1.41	1.54	1.44	1.34	1.3
Fillets, steaks	Head + trimmings + viscera removed	1.40	1.40	1.56	1.69	1.63	1.64	1.6
Skin on (fillets)	Head + frame + trimmings + viscera removed	1.64	1.64	1.92	2.13	1.92	2.23	2
Skin off	Head + frame + trimmings + skin + viscera removed	1.78	1.78	2.22	2.50	2.31	3.28	2
Fish salted, wet or in brine	Head + viscera removed	1.26	1.26	1.41	1.54	1.44	1.34	1.5
Fish prepared or preserved, canned	Head + trimmings + viscera removed	1.40	1.40	1.56	1.69	1.63	1.64	1.2
Smoked (skin off)	Head + frame + trimmings + skin + viscera removed	1.78	1.78	2.22	2.50	2.31	3.28	1.92

Aquaculture production statistics obtained from the FAO (2020d) are presented by country as tonnes LWE. On the other hand, data on trade is given on a commodity basis (e.g., “Atlantic and Dunabe salmons, fresh or chilled”, “salmon fillets, frozen”, “salmons, salted or in brine” etc.) in tonnes. The by-product volumes that are available in different countries can be estimated from the trade in different seafood commodities combined with production volumes. This is followed up by multiplying the commodity weight by the conversion factor (Table 4.1) resulting in the LWE volume, from which the commodity weight is subtracted to give the available by-product yield derived from the production of a specific commodity.

Assumptions

Processing practices vary between species and location. For the purposes of this report, it is assumed that all aquaculture products are eviscerated at the point of slaughter in the country of production to produce Head-On-Gutted fish (HOG), which is defined as “primary processing”. Further processing of HOG fish may occur within the country of production or after export, to produce fillets and steaks, which is termed “secondary processing”. In some circumstances, the BP generated from secondary processing such as trimmings and heads, may be further processed into pâtés, soups, ready meals etc, which is termed as “value addition”. The proportion of aquaculture supply that is completely (both primary and secondary) processed in the EEA is not possible to determine with accuracy from FAO data, although some estimations can be made using production and trade data together with other literature resources. For any single country and species, commodities and derived BP from exported commodities can be calculated if there is enough disaggregation within the commodity data. However, of the remaining production and any imports of HOG fish, the proportion that is secondary processed must be assumed. In Northern European countries (Table 4.2), where the preference is for fillets and more processed commodities, it is assumed that the left-over share is fully processed for most species, providing a maximum yield of BP for further utilisation. I assumed that Atlantic salmon is fully processed in all European import countries. However, I assumed that European seabass, gilthead seabream and turbot HOG imports into South European countries (Table 4.2) were not further processed, as consumers prefer to purchase whole fish over fillets, both for home consumption and in the service sector.

Table 4.2: List of Northern and Southern European countries.

Northern Europe			**Southern Europe**
Austria	Hungary	Norway	Croatia
Belgium	Iceland	Poland	France
Bulgaria	Ireland	Romania	Greece
Czech Republic	Latvia	Slovakia	Italy
Denmark	Liechtenstein	Slovenia	Malta
Estonia	Lithuania	Sweden	Portugal
Finland	Luxembourg	United Kingdom	Republic of Cyprus
Germany	Netherlands		Spain

Common carp is also usually sold whole and often live, therefore imports into east European countries were assumed mostly unprocessed. A full list of the assumptions on levels of processing is given in Table 4.3 and the differences become apparent in the balances given below. Commodities in FAO data sometimes include multiple aggregated species (e.g., “salmon fillets fresh or chilled”, “salmonoids frozen” and “carps, eels and snakeheads, fillets, fresh or chilled”) and sometimes a mixture of wild and aquaculture production. Consequently, individual species data can be challenging to disaggregate. Therefore, assumptions were made to determine the share of aquaculture vs fisheries and species composition within commodities, based on the proportion of production of those different species. For example, 85% of salmon commodities traded in the UK were estimated to come from UK farmed salmon, which was factored into the balance. Regional processing practices are given in Table 4.3. The assumptions used for processing practices are generalised according to indications given in the literature and from key informant stakeholders interviewed as part of CH3. For example, rainbow trout processing is averaged at 60% across Europe for simplicity, although most of it occurs in Northern countries associated with production of large sized fish.

Table 4.3: Quantity of EU and Norwegian aquaculture production accounted for in model and assumption of level of processing.

Species	**Aquaculture production accounted for %**	**Processing % in Northern Europe**	**Processing shares in Southern Europe**
Atlantic salmon	99	100*	100*
Rainbow trout	96	60	60
European seabass	97	100	5
Gilthead sea bream	95	100	5
Common carp	98	15	15
Turbot	100	5	5

** Filleted fish is assumed skin-on, whereas smoked fish is skin-off*

Aquaculture production, trade, and derived by-products

Seafood processing is highly diverse, often geographically displaced from production centres and recorded inconsistently, adding complexity to how the flows are calculated. For example, although Norwegian salmon is all slaughtered and “primary processed” in-country to produce HOG Atlantic salmon with viscera as a BP, only some of the HOG is further processed to fillets or other commodities in Norway. A larger proportion of HOG is exported for further processing across Europe, particularly Eastern Europe such as Poland, which is a major “secondary processing” centre, generating a large proportion of by-products. Therefore, although Norway is the largest producer of salmon, it is not the largest centre for potential value addition to by-products.

Example of by-product balance applied to the UK Atlantic salmon industry

A detailed example of by-products generated from UK salmon production and trade is given in Figure 4.1 and 4.2, with special references to Tables 4.4 to 4.7. The UK was selected as an example, because of the high volumes of domestic Atlantic salmon production, as well as imports and export of salmon commodities. The methodology shown in the following section was applied to all species, following the assumptions laid out in the previous section.

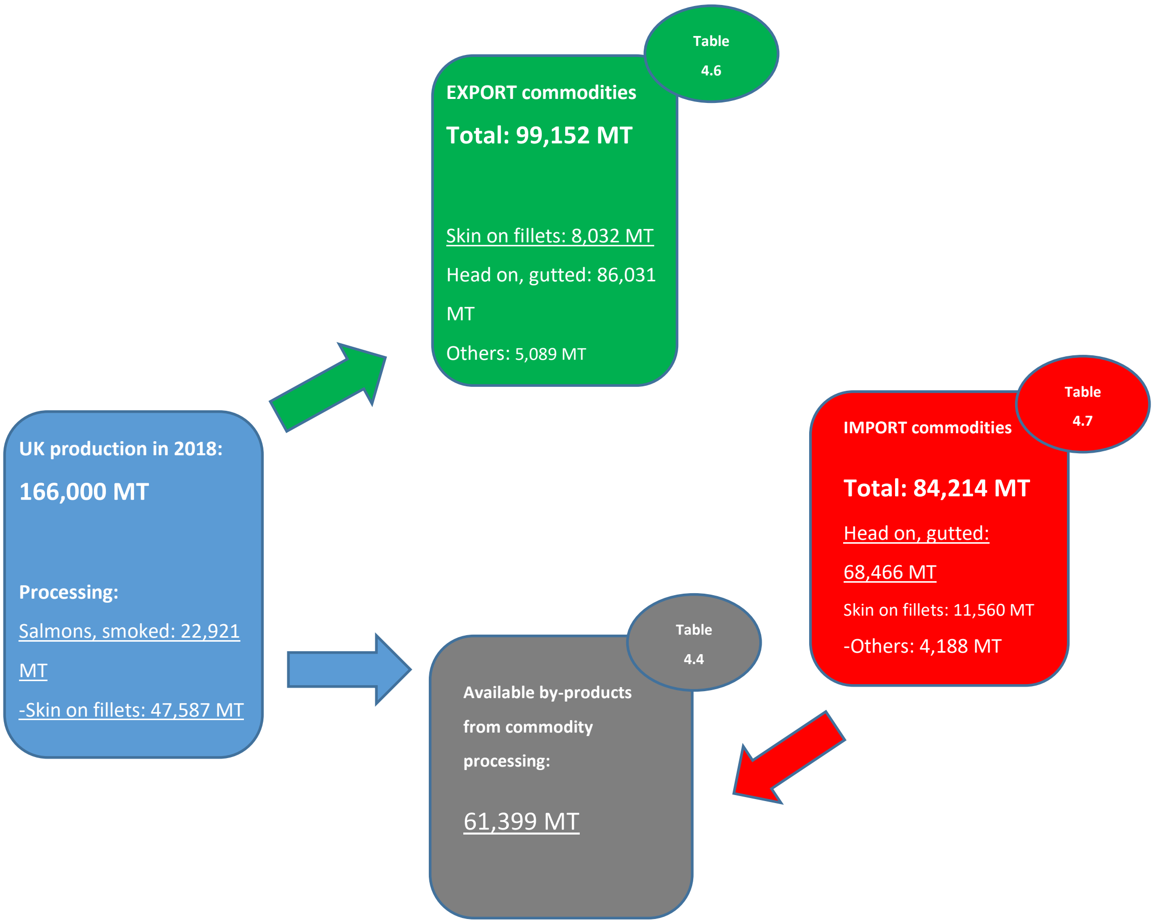


Figure 4.1: Flowchart UK Atlantic salmon, production, trade, and derived by-products.

Table 4.4: Available by-product volumes (MT) from production, import and export associated processing in 2018.

Available by-products from commodities	Aquaculture production*	Import**	Export***	Total BP generated
Heads	7,426	5,751	1,520	14,697
Frames	7,784	6,028	1,593	15,405
Trimmings	6,099	4,723	1,247	12,069
Skin	1,633	-	-	1,633
Viscera	17,595	-	-	17,595
Total	**40,537**	**16,502**	**4,360**	**61,399**

** By-products from UK production not traded but assumed to be fully processed.*
*** Resulting from processing of HOG salmon imported to UK.*
**** Resulting from processing of fish in the UK to produce fillets and other products for export.*

The United Kingdom produced 166,000 MT, LWE Atlantic salmon in 2018. Due to the nature of FAO reporting, all calculations are made in reference to LW production, whereas in reality, all of the production is primary processed to HOG and then either further processed or exported. Therefore, care must be taken when converting between LW and HOG that the volumes of viscera are not double counted, especially when dealing with traded products. The steps in the calculation are as follows:

i) Calculate the quantity of viscera generated from primary processing by applying the conversion factor (CF) for HOG to UK production.
ii) Calculate the quantity of by-products generated from secondary processing of commodities exported from the UK according to CF's.
iii) Calculate the quantity of by-products generated from imported commodities to the UK (HOG) according to CF's.
iv) Calculate by-products from secondary processing for UK domestic consumption according to CFs and assumptions from literature.
v) Make adjustments for viscera not produced within the UK from imports and for double counting errors associated with LW/HOG CF's.
vi) Calculate extra by-product potential if processing was optimised.

For example, for UK Atlantic salmon, domestic processing by-products were calculated as a proportion of LW according to the CFs to produce smoked salmon, fillets, and other commodities (Table 4.5). The resulting by-product volume from processing was divided between viscera, heads, trimmings, frames, and skin (Table 4.5). Imports of "whole fish" (HOG) were assumed to be fully processed into commodities and by-products, calculated according to their conversion factors and various fractions given in Table 4.7. The viscera from imported HOG remains in the country of primary processing/ production whereas secondary processed commodities exported from the UK have associated volumes of by-products which are left within the UK. However, the CFs for commodities processed from imported fish are based on LW and not HOG. Therefore, after all the commodities were calculated, including post trade, an adjustment, was made to prevent double counting of viscera volumes from traded products. The extra potential by-product volumes are estimated from the difference between the extrapolated volumes and those if all EU and Norway processing was at 100%. The traded commodities for Atlantic salmon according to the FAO (2020d) are shown in Tables 4.6 and 4.7. The different commodities traded per species and selected countries based on production, import and export, are listed in Appendix A2.1-A2.6.

Table 4.5: By-product fractions from UK smoked salmon production (2018) as a proportion of LW and of total by-product.

Origin – By-products from processed production (smoked salmon)	**Fraction of LWE**	**Fraction of total by-product**	**MT in 2018**
Heads	10%	23%	3,447
Frames	10%	24%	3,613
Trimmings	8%	19%	2,831
Skin (incl. scales)	5%	11%	1,641
Viscera	11%	24%	4,326
Total	**44%**	**100%**	**15,858**

Table 4.6: Conversion factors, export commodity weights and extrapolated LWE for Atlantic salmon.

Processing	**CF**	**Commodity (Commodity)**	**Commodity weight (MT in 2018)**	**LWE MT (2018)**
Gutted, head on (HOG)	1.12	Atlantic and Danube salmons, fresh or chilled	74,816	83,686
Gutted, head on (HOG)	1.12	Atlantic salmon and Danube salmon, frozen	6,158	6,888
Skin on	1.64	Salmon fillets, dried, salted or in brine	113	186
Skin on	1.64	Salmon fillets, fresh or chilled	6,595	10,831
Skin on	1.64	Salmon fillets, frozen	1,324	2,174
Fish prepared or preserved, canned	1.40	Salmon minced, prepared or preserved	156	219
Gutted, head on (HOG)	1.12	Salmon nei, not minced, prepared or preserved	1,394	1,559
Gutted, head on (HOG)	1.12	Salmonoids meat, fresh or chilled, nei	226	253
Fish prepared or preserved, canned	1.40	Salmonoids nei, minced, prepared or preserved	6	8
Gutted, head on (HOG)	1.12	Salmonoids, fresh or chilled, nei	1,978	2,213
Gutted, head on (HOG)	1.12	Salmonoids, frozen	1,422	1,591
Gutted, head on (HOG)	1.12	Salmonoids, not minced, prepared or preserved	37	41
Whole fish	1.00	Salmons, live	11	11
Smoked	1.78	Salmons, smoked	4,916	8,753

Note: CFs presented here are rounded to two decimal points but those used to calculate the model were not rounded

Results were verified by calculating the share of each by-product (MT) as part of the total aquaculture production (MT) (Table 4.4). This share was then compared with all the by-product fractions obtained from the lab analysis of Malcorps *et al.* (2021c).

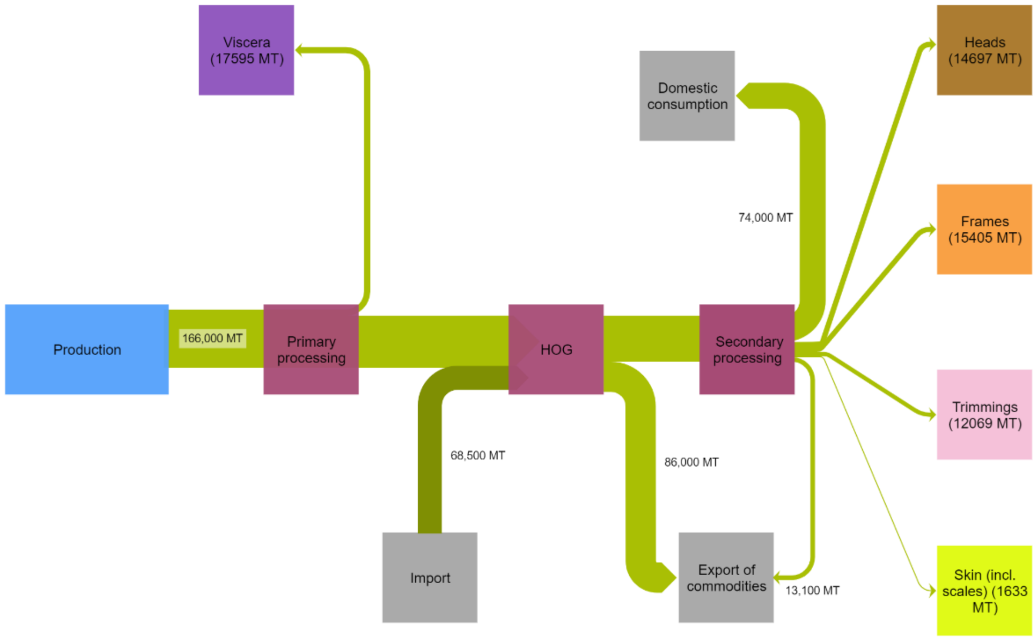


Figure 4.2: Material flows of co-products from UK farmed salmon production and processing in 2018. Created by the author with Sankey diagram.

Table 4.7: Volume of UK salmon import commodities.

Processing	**Commodity (Commodity)**	**MT in 2018**
Gutted, head on (HOG)	Atlantic and Danube salmons, fresh or chilled	57,543
Gutted, head on (HOG)	Atlantic salmon and Danube salmon, frozen	178
Skin on	Salmon fillets, fresh or chilled	3,568
Skin on	Salmon fillets, frozen	7,992
Fish prepared or preserved, canned	Salmon minced, prepared or preserved	636
Gutted, head on (HOG)	Salmon nei, not minced, prepared or preserved	10,621
Gutted, head on (HOG)	Salmonoids, fresh or chilled, nei	14
Gutted, head on (HOG)	Salmonoids, frozen	110
Fish prepared or preserved, canned	Salmons, salted or in brine	344
Smoked	Salmons, smoked	3,208

In the case of the UK total salmon, the assumption was that there was 100% processing across the EU and no further potential for increasing by-product volumes within the EU. However, aquaculture production was 166,000 MT in 2018, while available by-products volumes from current processing activities were estimated at 61,399 MT, representing a share of 37%. Around 4% availability could be added from deskinning fillets and non-EU/Norway trade accounts for the other remaining by-product fractions, equalling the expected 44% from Table 4.5.

By-product processing volumes and applications

The available by-product volumes were assessed for the quantities of flesh that could be obtained for human consumption (assuming total efficiency of removal) and their application in, e.g., fish protein hydrolysate (FPH) and peptones, amongst others. The flesh yields were taken from a published lab analysis by Malcorps *et al.* (2021c), available in section 4.3.2 in table 4.12, whereas yields of FPH, peptones and FO can be found in Appendix A2.7-A2.10. Some products were produced from a single by-product fraction, e.g., seabass heads, while others were produced from a mix of by-products such as frames and trimmings, but not in the proportions generated from whole fish. In that case, one of the by-products becomes a limiting factor for the process. Although, the remaining by-product could be applied elsewhere, this was not calculated because of the many different options. For example, Atlantic salmon frames and trimmings are produced in volumes of 16,537 MT and 12,956 MT respectively. The salmon FPH production process applied used a mix of 80% frames and 20% trimmings leaving a remainder of 8,822 MT salmon trimmings from the process.

4.2.2 Nutritional characterisation of aquaculture processing by-product in Europe

Triplicate samples of heads, frames (the central skeleton of the fish including the tail), trimmings, skin (incl. scales) and viscera of Atlantic salmon, European seabass and gilthead seabream were obtained from commercial processors in Norway and Spain, whereas by-products of turbot and carp were provided by local producers in Spain and Poland, respectively, to commercial specifications. All species were fed formulated feed, except for common carp, which was grown on a natural diet with low levels of cereal supplementation. The fish from which the by-products originated were weighed before processing to calculate the share of each by-product. By-product components were frozen, weighed, packed, and transported on ice in polystyrene boxes by air freight. The analyses were performed at the Institute of Aquaculture (University of Stirling), using internationally recognized analytical procedures and calibration standards (ISO, 2005; AOAC, 2005). All samples were kept frozen at -20 °C until analysed.

Flesh yields of the by-products

The samples were weighed (precision +/-0.01g) before removing the edible flesh from each by-product fraction (except viscera) with a scalpel. The weight of the removed flesh was subtracted from the total weight of the by-product to determine the flesh yield (%). After completion, separated flesh and other parts were recombined for each separate sample and homogenised for further analysis.

Proximate analyses

The proximate composition of samples was determined using standard methods (AOAC, 1990). Moisture content was determined by weighing ~ 1 g of homogenised wet sample and placing into a drying oven for 20 h at 105 °C. Ash content was determined by weighing ~ 1 g of dried sample and placing into a muffle furnace overnight set at 600 ºC. Crude protein was measured by weighing ~ 0.25 g dried sample before addition of copper catalyst tablets and 5 ml sulphuric acid (analytical reagent grade, Fisher Scientific, Loughborough, UK). Samples were digested at 400 ºC for 1 h (Foss Digestor 2040, Foss Analytical AB Högnäs, Sweden). Total nitrogen levels were measured by Kjeldahl (Foss Kjeltec™ 2300, Foss Analytical AB, Högnäs, Sweden) and the crude protein level calculated as N × 6.25. The moisture content was used to convert results to a wet weight basis. Total lipid was extracted from homogenised wet samples using 20 vol of ice-cold chloroform/methanol (2:1, v/v) using an Ultra-Turrax tissue disruptor (Fisher Scientific, Loughborough, UK) according to (Folch, Lees and Sloan Stanley, 1957). Non-lipid impurities were isolated by washing with 0.88% KCl and the lipid weight determined gravimetrically after evaporation of solvent using oxygen-free nitrogen and desiccation *in vacuo* before making up to a known concentration and storing at –20 ºC.

Fatty acid analysis

The fatty acid (FA) profile of samples were determined by fatty acid methyl esters (FAME) prepared from total lipid extracts that had undergone acid-catalysed transmethylation at 50 ºC for 16 h using 2 ml 1% (v/v) sulphuric acid (95%, Aristar, BDH Chemicals, Poole, UK) in methanol and 1 ml toluene (Christie, 2003). FAME were extracted and purified according to (Tocher and Harvie, 1988) and separated and quantified by gas-liquid chromatography. Individual FAME were identified by comparison to known standards (in-house marine oil and Restek 20-FAME Marine Oil Standard; Thames Restek UK Ltd., Buckinghamshire, UK), in addition to published literature (Tocher and Harvie, 1988; Ackman, 1980). Data were collected and processed using Chromcard for Windows (Version 2.11; Thermo Fisher Scientific Inc., Milan, Italy). Fatty acid content per g sample was calculated using heptadecanoic acid (17:0) as internal standard.

Statistics

Results were analysed using Minitab® v18.1 statistical software package (Minitab Inc., Pennsylvania, USA). Comparisons were made by Analysis of Variance (ANOVA; General linear model with Tukey Pairwise comparisons) between the triplicate samples (five species and five by-products) on a flesh yield, proximate composition, and EPA+DHA resolution.

4.2.3 Case study common carp: value-added through strategic fish processing

The initial results from the common carp (Poland) KI survey identified opportunities for developing the primary and secondary processing sector in Poland. Common carp in Poland is mostly sold live or sometimes in traditional product forms, such as fillets, slices, and sheets (Figure 4.3) and whole carcasses (beheaded and gutted only). Increased processing may lead to an increase in economic output of the industry. This model looks at the added value but does not include costs associated with the utilisation of the by-products, such as ice, packaging, and labour.

Figure 4.3: Common carp sheet (single flap, one side of carcass cut along the spine with skin and ribs on) and carp slice (lateral steaks, carp cut perpendicularly to the spine from the top of the carcass to the ventral part, thickness of approx. 2cm). (Photo left by Piotr Eljasik, photo right by Marco Verch Professional Photographer, https://www.flickr.com/photos/30478819@N08/48609383168, CC BY 2.0 DEED, no changes made).

To maximise the volume output beyond traditional product forms such as those indicated in Figure 4.3, full processing is desired, which would include the slaughter and removal of the viscera and head (primary processing) and the separation of the fillets and by-products (secondary processing). This shows potential in Poland (Raftowicz and Le Gallic, 2019), as well as from the KI and panel of experts in CH3, from both an economic, environmental and fish welfare perspective, as 1) fish do not suffer, but are slaughtered fast and efficiently according to established protocols; 2) less resources are need as the whole animal is used more efficiently.

Compared to traditional processed product forms, full processing not only results in high value fillets, but also in the additional availability of by-products, such as trimmings and frames. Nevertheless, processing into traditional product forms and fillets results in more by-product availability at the processor level, compared to live or whole fish sales. To understand the additional economic value that might be obtained from these by-products, an Excel spreadsheet model that compared different processing scenarios into various amounts of different product forms was developed. Therefore, it was important to understand the logistics of carp production chains in Poland, to enable structural changes (Lirski, 2021a), and the preferred product/consumption forms (Raftowicz *et al.*, 2019) (Table 4.8). Based on the current preferred product forms (e.g., live carp, sheet, or slices), different processing scenarios were developed representing “business-as-usual” scenarios and gradually moving towards a complete (primary and secondary) processing scenario (Tables 4.8 and 4.9). Scenarios 1 to 5 included traditional processing and consumption of carp, such as slice and sheet (Figure 4.3) assuming that by-products are discarded or consumed by human and/or animals at the household level and are marked red (Table 4.9). On the other hand, Scenarios 6 to 10 included new product forms that substitute traditional product forms (e.g., living carp).

Table 4.8: Description of processing scenarios.

S.		**Description of processing scenarios into different product forms**
Commodities	1	Mostly consumption of live common carp with small proportion being processed (by-products at household level) (yield 100%)
	2	Common carp gutted (yield 84.3%)
	3	Carcass[1] – common carp beheaded and gutted (yield 60.3%)
	4	Slice[2] – common carp beheaded and gutted (yield 58.1%)
Combination	5	Common carp beheaded, gutted and partly de-framed (yield 44.2%)
	6	Combination of live sales and processed – 80% live + (20% sheets[3] incl. by-products)
	7	Combination of 55% live + (30% filet incl. by-products) + (15% carcass incl. by-products
	8	Combination of 40% live + (40% filet incl. by-products) + (20% carcass incl. by-products)
	9	Based on an achievable scenario – 20% live + (80% sheets[3] incl. by-products)
Objective	10	40% Fillets + (incl. 60% by-products such as heads, frames, trimmings, skin, and viscera) – strategic utilisation

[1] *Carcass: beheaded and gutted*

[2] *Slice: carp cut perpendicularly to the spine from the top of the carcass to the ventral part, thickness of approx. 2cm. (Figure 4.3)*

[3] *Sheet: (single flap) one side of carcass cut along the spine with skin and ribs on (Figure 4.3).*

The different processing scenarios result in a variety of co-product yields as listed in Table 4.9. The traditional product forms of Scenarios 1 to 5 (in red) assume that by-products are not used, whereas full utilisation is assumed in Scenarios 6 to 10. Yields may slightly differ depending on the processing product form and initial yield of the main products. More specifically, in the case of some by-products such as frames, part of the by-product is removed and therefore the share of each by-product may slightly differ depending on the processed product form.

More specifically, in the case of some by-products like frames, part of this by-product is taken in the case of e.g., carp sheet processing (Figure 4.3: single flap, one side of carcass cut along the spine with skin and ribs on). Therefore, the share of each by-product could slightly differ depending on the processed product form. The product forms and related prices were combined to understand the economic potential of the diversification of different product forms. Additionally, by-products could be utilised in a range of applications, from food to feed and industrial applications. Prices were obtained from the carp industry in the local currency (Polish złoty (zł, PLN)) with expert advice from ZUT researchers (Table 4.10). At the time of writing, 1 PLN is equal to 0.22 euro. The estimated prices (Table 4.10) assume that by-products directed into food applications have a higher value, followed by feed applications, especially pet food, and other industrial applications. According to the fish by-product hierarchy pyramid in the paper of Stevens *et al.* (2018), waste reduction and food recovery should have the highest priority, followed up by animal feed and industrial applications. If by-products are not suitable for animal feed or food, or a higher economic value can be generated, industrial applications could be suitable. The lowest value option, which may often incur a charge, is composting or discarding to landfill. It is assumed that if by-products are sold, they are all sold due to economic incentives of higher volume transportation and utilisation. I assumed that discard of by-products for composting/fertilizer is free, although some farmers indicated that they paid a premium charge to dispose fish by-products into landfill, as part of the use of environmental taxes and charges in the European Union and its member states (EC, 2001).

In total seven utilisation pathways were identified based on the price data accessed from farmers, processors, and researchers, namely: 1) market price, 2) average, 3) food, 4) feed, 5) industrial users, 6) composting/fertilizer, and 7) landfill/incineration (Table 3.11). Product yields and market prices were obtained from the literature (Lirski, 2021a) and discussed with researchers from ZUT and slightly adjusted. The prices for the by-products (heads, frames, trimmings, viscera, and skin) were obtained from stakeholders in the field and expert opinion of researchers active in the Polish carp value chain. “Average” represents the average price of food, feed, industrial use, composting/fertilizer, and landfill incineration where individual prices could not be estimated (Table 4.11).

Table 4.9: Scenarios and co-product yields.

Scenario	**Co-product yields (%)**											
	Live carp	**Gutted**	**Carcass**	**Slices**	**Sheet**	**Fil-lets**	**Heads**	**Frames**	**Trim-mings**	**Skin (incl. scales)**	**Viscera**	**SUM (% utilised)**
1) Traditional	**100.0**	**-**	**-**	**-**	**-**	**-**						**100**
2) Gutted	**-**	**84.3**	**-**	**-**	**-**	**-**					15.7	**84**
3) Carcass[1]	**-**	**-**	**60.3**	**-**	**-**	**-**	24.0				15.7	**60**
4) Slice[2]	**-**	**-**	**-**	**58.1**	**-**	**-**	25.1				16.8	**58**
5) Sheet[3]	**-**	**-**	**-**	**-**	**44.2**	**-**	24.0	16.1			15.7	**44**
6) Possible Scenario	**80.0**	**-**	**-**	**-**	**8.8**	**-**	**4.8**	**3.2**	**-**	**-**	**3.1**	**100**
7) Business as Usual (Actual Form[4]	**55.0**	**-**	**9.0**	**-**	**-**	**13.0**	**8.8**	**2.8**	**2.4**	**2.6**	**6.4**	**100**
8) Preferred Scenario[4]	**40.0**	**-**	**12.1**	**-**	**-**	**17.3**	**11.7**	**3.7**	**3.2**	**3.5**	**8.5**	**100**
9) Achievable Future Scenario[4]	**20.0**	**-**	**-**	**-**	**35.4**		**19.2**	**12.9**	**-**	**-**	**12.6**	**100**
10) Fully Processed and Utilised[4]	**-**	**-**	**-**	**-**	**-**	**43.3**	**17.3**	**9.3**	**8.0**	**8.7**	**13.5**	**100**

In red: underutilised by-products in Scenarios 1 to 5 at processor level or household level: these are discarded.
[1]*Carcass: beheaded and gutted.*
[2]*Slice: carp cut perpendicularly to the spine from the top of the carcass to the ventral part, thickness of approx. 2cm.*
[3]*Sheet: (single flap) one side of carcass cut along the spine with skin and ribs on.*
[4]*"Business as usual", "preferred scenario", "achievable future scenario" are market based on previous work and conversations with scientist in the field.*

Price for whole live carp for 2019 was obtained from the literature in a Polish fish processing magazine (Hryszko, 2021). Additionally, yields and prices (including other costs, such as labour, packaging, ice) of traditional carp products were based on Lirski *et al.* (2020) and discussed and adjusted in consultation with researchers from ZUT (Table 4.10 and 4.11).

Table 4.10: Prices of carp by-product fractions provided by stakeholders of the Polish value chain.

	(Included: prices of labour, ice, and packaging)	**(Excluded: prices of labour, ice, and packaging)**						
***By-products (PLN/kg) utilisation data**	**Processor 1***	**Processor 1**	**Fish farm 1**	**Fish farm 2**	**Fish farm 3**	**Fish farm 4**	**Resear-cher 1**	**Resear-cher 2**
Heads	5	-2	1.25	0	-0.9	-3	2.5	3
Frames	6.3						2.5	
Trimmings	-						2.5	
Skin (incl. scales)	10						2.5	
Viscera	-						2.5	

**All prices are obtained from the farm gate level. However, the first row are prices that a specific processor obtained by buying whole carp and selling its co-products to the consumers and is therefore considered as value addition. Negative values indicate associated costs with the disposal of the by-products.*

Table 4.11: Carp (by-)product forms and prices.

(By-)product Utilisation Pathways									
	Advised		**[3]In "grey" price (PLN/kg) of by-products obtained at farm or processor level, utilised in different applications**						
[1]Products	**[1]Estimated Yield (%)**	**Market Price (PLN/kg)**	**Average**	**Food (excl. viscera in feed)**	**Feed**	**Industrial Users (excl. viscera in feed)**	**[4]Composting/Fertilizer**	**Landfill/Incineration**	
Live carp (fresh)	**100**	**[1]8.83**	-	-	-	-	-	-	
Gutted	**84.3**	**[1]10.19**							
Carcass (beheaded and gutted)	**60.3**	**[1]14.25**	-	-	-	-	-	-	
Slice	**58.1**	**[1]14.79**	-	-	-	-	-	-	
Sheet	**44.2**	**[1]19.44**	-	-	-	-	-	-	
Filet	**40.1**	**[1]21.45**	-	-	-	-	-	-	
Filet	**[2]43.3**	**[1]21.45**	-	-	-	-	-	-	
Heads	**[2]17.3**	**2.8**	**1.6**	**3.5**	**1.3**	**5.0**	**0.0**	**-2.0**	
Frames	**[2]9.3**	**2.8**	**1.9**	**3.9**	**1.3**	**6.3**	**0.0**	**-2.0**	
Trimmings	**[2]8.0**	**2.8**	**1.0**	**2.8**	**1.3**	**3.0**	**0.0**	**-2.0**	
Skin (incl. scales)	**[2]8.7**	**2.8**	**2.9**	**5.2**	**1.3**	**10.0**	**0.0**	**-2.0**	
Viscera	**[2]13.5**	**2.8**	**0.4**	**1.3**	**1.3**	**1.3**	**0.0**	**-2.0**	

[1] Price for whole live carp for 2019 obtained from the fish processing magazine in Poland (Hryszko, 2021). Yields and prices of traditional carp products (incl. other costs, such as labour, packaging, ice, etc.) are based on (Lirski, 2020) and discussed and slightly adjusted in consultation with researchers from ZUT. Yields could slightly differ depending on the initial scenario and initial yield of the main products. They could be slightly adjusted to add up to 100% utilisation.

[2] Malcorps et al. (2021c)

[3] Prices of Table 4.10 are allocated in Table 4.11 based on price expectations for different pathways, e.g., higher price for food compared to feed etc. Assumption: all by-products are sold due to economic incentives of higher volume transportation and utilisation.

[4] Assume that discard of by-products for the use of composting/fertilizer is for free. Collecting for free was indicated by "fish farm 2" in Table 4.10.

4.3 Results

4.3.1 Identifying by-product volumes in Europe

Processing, business as usual and additional potential

Available by-product volumes are dependent on the level of processing and fish production volumes, which differs according to species, in combination with the fraction of each fish by-product in relation to its total body weight. Processing potential indicates the additional potential that can be realized if full processing is implemented. Earlier results published in the study of Malcorps *et al.* (2021c) indicated that Atlantic salmon have the largest fillet yield of the species studied, at approx. 56%, down to turbot with only 30% fillet yield.

Figure 4.4 indicates potential to increase the level of processing and hence, the availability of by-products. Salmon showed the highest level of processing, with only limited extra volumes of heads, frames, trimmings, and viscera possible, linked to non-EU traded products. More skin could be made available by an increase in smoked salmon production compared to skin-on fillet commodities. Consumer preference for skin on or off was not assessed. Rainbow trout was assumed to have similar fillet yields to Atlantic salmon. Availability of viscera was at full potential for all species except carp because it is the only species sold live, while skin showed greatest potential for separation, assuming consumer preferences for skin-off fillets.

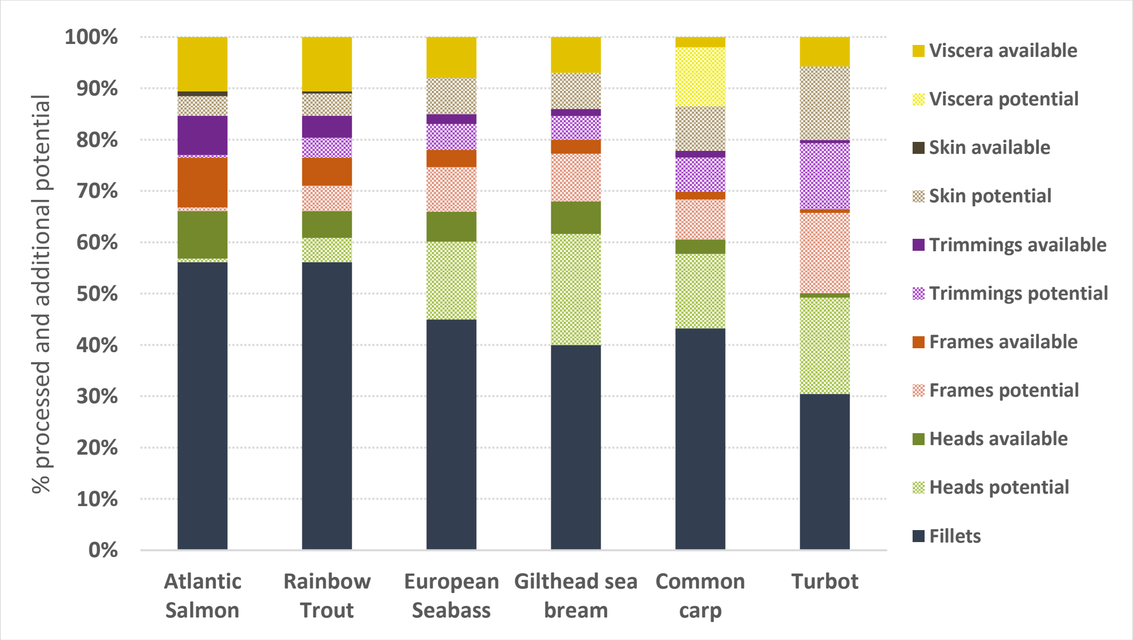


Figure 4.4: Available by-products and potential additional availability from processing for major European aquaculture species in 2018. Pattern fill indicates unrealised processing potential.

However, consumer preferences for whole fish (HOG) in the South of Europe was assumed to result in low levels of secondary processing of European seabass, gilthead seabream and turbot, and therefore lower volumes of by-products of those species were available for strategic utilisation. Increase in processing could result in an increase of total yield to LWE ranging between 0.64% and 21.62% for heads, 0.67% and 15.65% for frames, 0.52% and 12.85% for trimmings, 3.80% and 14.30% for skin and 0% up to 11.44% for viscera (Figure 4.4).

Available by-product volumes based on business-as-usual processing and trade

The following section highlights the main results from the by-product balance and the potential feed ingredients that could be produced from this supply.

Atlantic salmon

There are large volumes of viscera from primary processing at the point of slaughter within Norway, but secondary processing is decentralised to countries with large fish processing industries such as Poland and Lithuania that are not large producers of salmon (Figure 4.5). This explains why there is no viscera available in Poland (Denmark, France, and Germany), but are large volumes of heads, frames, and trimmings. Poland also shows the largest proportion of fish skin availability from smoked salmon processing. The United Kingdom imports around the same volume of HOG salmon as it exports, so the proportions of by-products are close to those given in Table 4.4.

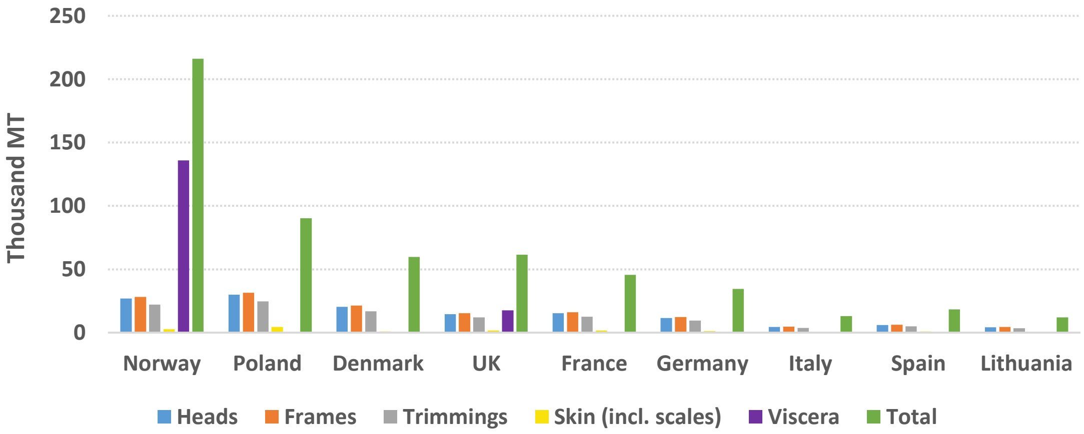


Figure 4.5: Available Atlantic salmon by-products by country (2018).

Rainbow trout

Rainbow trout is produced across Europe. Norway was the largest producer with 68,216 MT in 2018. Resulting in the largest proportion of viscera from primary processing (Figure 4.6), followed by Italy, Denmark, and France. However, while Norway is the largest producer, France has a larger volume of secondary processing by-product volume available due to the processing of HOG imports. The volumes of rainbow trout skin in Denmark and France are the direct result of smoking in those countries.

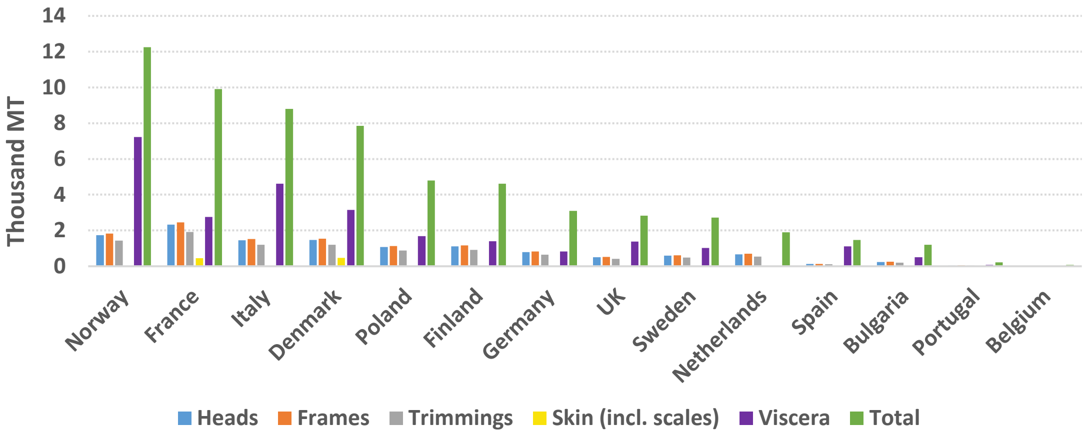


Figure 4.6: Available rainbow trout by-products by country (2018).

European seabass

Greece is the largest producer of European seabass in the EU, followed up by Spain resulting in the highest viscera volumes from primary processing (Figure 4.7), but the preference for consuming whole (gutted) fish in Southern European countries means there is little or no secondary processing of by-products from domestic processing. Conversely, exports of HOG seabass to Northern European countries are assumed to be fully processed to fillets resulting in their respective available by-products volumes (Figure 4.7). However, the FAO data contains no reference to seabass fillet exports which must be aggregated within another commodity, which was not possible to determine. Therefore, there are no secondary by-products resulting from filleting in Southern European countries for export, according to the model.

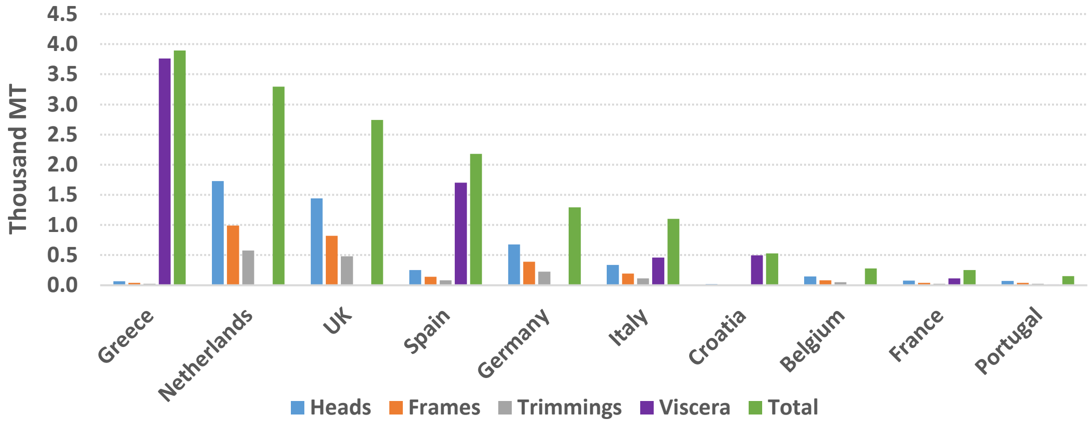


Figure 4.7: Available European seabass by-products by country (2018).

Gilthead seabream

Greece is the largest producer of sea bream in Europe, leading to high volumes of viscera from primary processing. Greek exports are higher than production, explained by its significant import volumes (particularly from Turkey), that are re-exported with no further processing. However, like European seabass, producing countries have little secondary processing, so most heads, frames and trimmings are generated within importing countries where consumers prefer fillets according to the assumptions in the model (Figure 4.8).

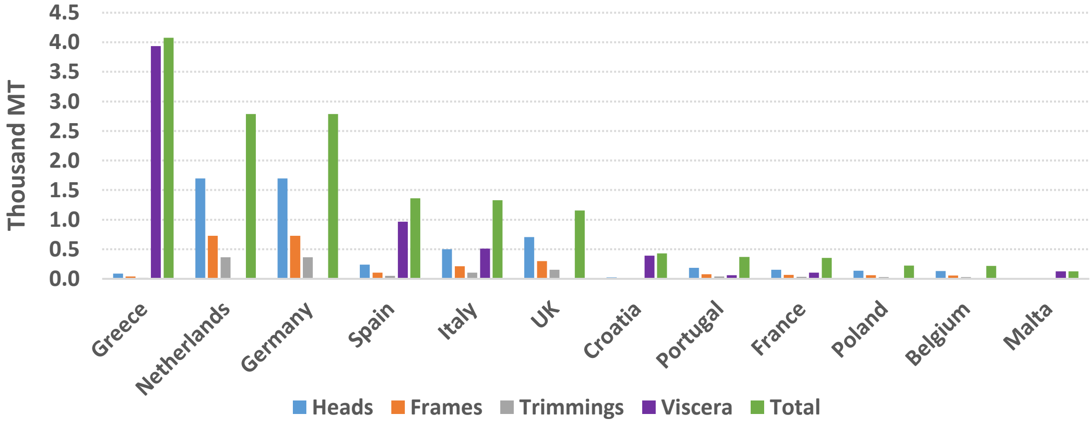


Figure 4.8: Available gilthead seabream by-products by country (2018).

Common carp

Total common carp production was 74,554 MT in the EU in 2018, but processing is not a common practice due to consumer preferences for whole fish, even across Northern Europe, where sales are often to satisfy eastern European diaspora. Preference for live fish in producer countries explains the low available volumes of viscera (Figure 4.9). However, there is a small but growing movement towards more processed commodities, away from live sales due to welfare concerns amongst some consumers. According to FAO (2020), 2,796 MT of carp fillets were exported from Spain in 2018, from which the by-product supply is extrapolated, whereas Poland exports less processed products and most of the heads, frames and trimmings are extrapolated from domestic consumption, assumed to be secondary processed at 15% (Table 4.3).

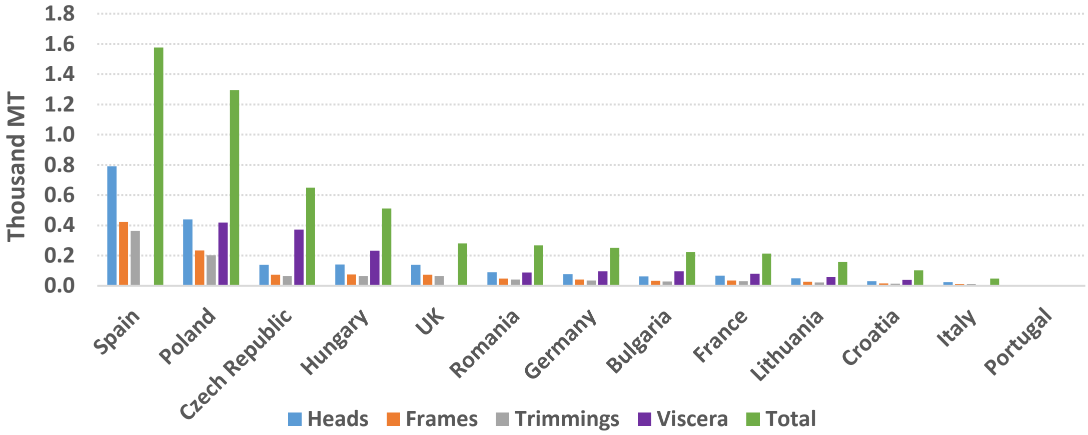


Figure 4.9: Available common carp by-products by-country (2018).

Turbot

Turbot is a niche species with low production volumes in the South of Europe. The majority is sold whole, sometimes without gutting and consequently by-product volumes are very low (Figure 4.10). The available by-product volumes in Northern European countries are related to the imports of HOG turbot, from which small volumes are processed into fillets. It is assumed that much of the imports are unprocessed, going to service sectors rather than retail.

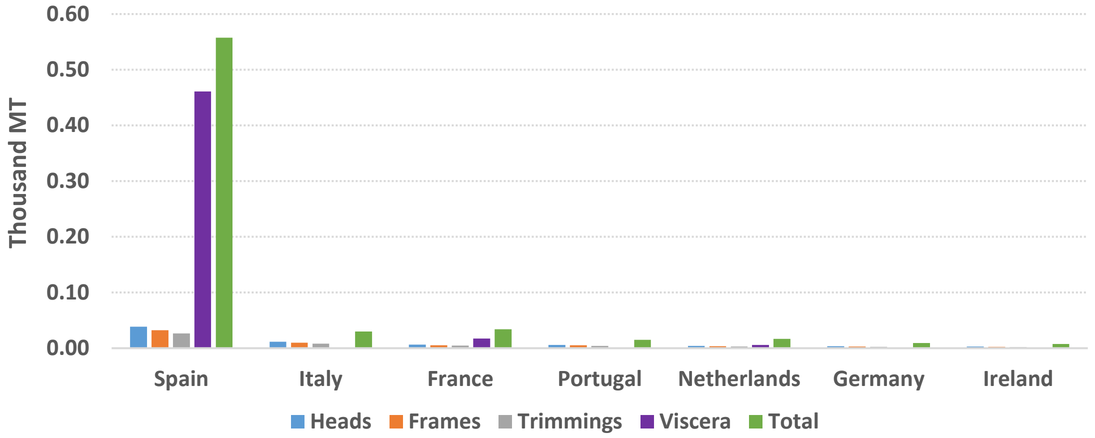


Figure 4.10: Available turbot by-products by country (2018).

Value addition potential from EU processing aquaculture by-products

Value addition can be achieved by extraction more flesh from the by-products. However, high value products could also be produced, such as FPH, peptones and oils. The yields of these high value products were provided by IIM-CSIC to further calculate the potential production volumes.

Flesh recovery for direct human consumption

Whether flesh recovery is a feasible option from by-products is likely to be determined by the quantity of by-products, their quality, and consistency of production. Skin is assumed to be 100% edible, whereas viscera are assumed to have no edible fraction. How flesh could be obtained from by-products is open to debate according to processing practices and consumption patterns. Where, fish is bought whole and prepared within the home, it may be argued that all the edible parts may be consumed directly, although this may be considered unlikely if some is particularly difficult to separate, such as in heads of some of the smaller fish species. The bones, eyes and other soft tissues are also not likely to be consumed, whereas if directed to marine ingredients, more nutrition and value could be obtained. Mechanised flesh recovery from processed by-products may also be challenging, especially from smaller species. Typically, recovered flesh may be used for value added products. Processed salmon heads are commonly exported to Vietnam and other East Asia countries for use in their local cuisine, but heads of other species are not, perhaps due to their smaller size as well as their availability. Processing can, in some circumstance, allow for better use of by-product resources, but in other circumstances more direct flesh consumption may be achieved through leaving the fish whole. The relative efficiencies have not been assessed, but it is likely that with better separation and targeting of by-product resources, more efficiency can be achieved as discussed by Stevens *et al.* (2018). The following graphs show the total edible flesh yields from each by-product fraction in each country.

Atlantic salmon

There is also a lot of capacity across Europe to increase the flesh yield from by-products at over 220 thousand tonnes, outstripping UK production (Figure 4.11). However, much of this is already done through reclamation from trimmings, export of heads and to a lesser extent, frames. Nevertheless, Stevens *et al.* (2018) estimated that around 50% of by-products remain mixed and are destined for rendering and hydrolysis in the marine ingredients industry, which could be separated and used for human consumption with potential value addition.

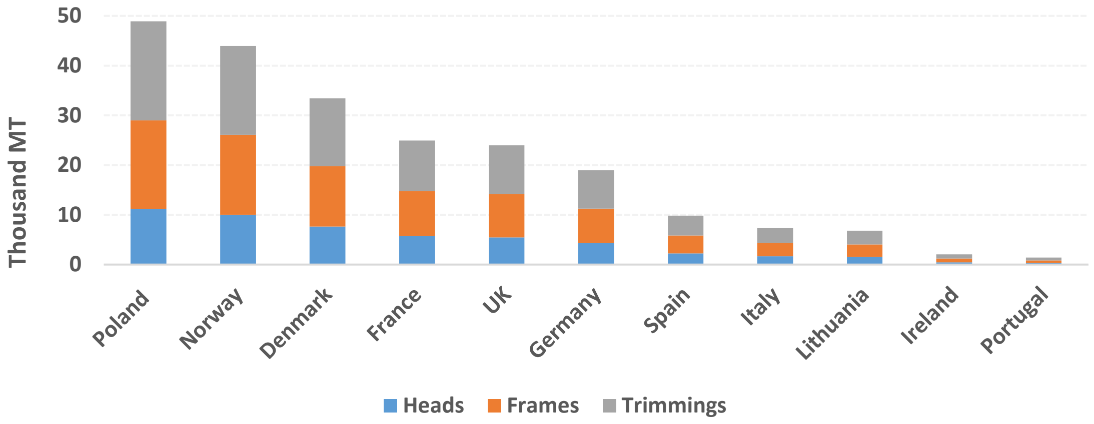


Figure 4.11: Potential flesh yield from Atlantic salmon processing by-products.

Rainbow trout

Despite being a widely produced species, the potential for more flesh yield from Rainbow trout is quite low, owing to low processing levels and sale of HOG fish. The major processors in France, Norway and Italy have the highest potential for reclaiming flesh although processing is much more geographically dispersed, with several countries producing modest quantities of by-products (Figure 4.12). However, feasibility of reclamation may depend on the size of fish. Trout are produced in a much wider range of sizes compared to salmon, from 500 g to several kilos and smaller fish may be too difficult to obtain meaningful quantities of flesh and better directed to marine ingredients production. According to EUMOFA (2017), around 40% of trout production is large sized and processed to fillets and other products, with most of the production occurring in Northern European countries. However, the model assumed 60% processing across all countries because of problems disaggregating the data.

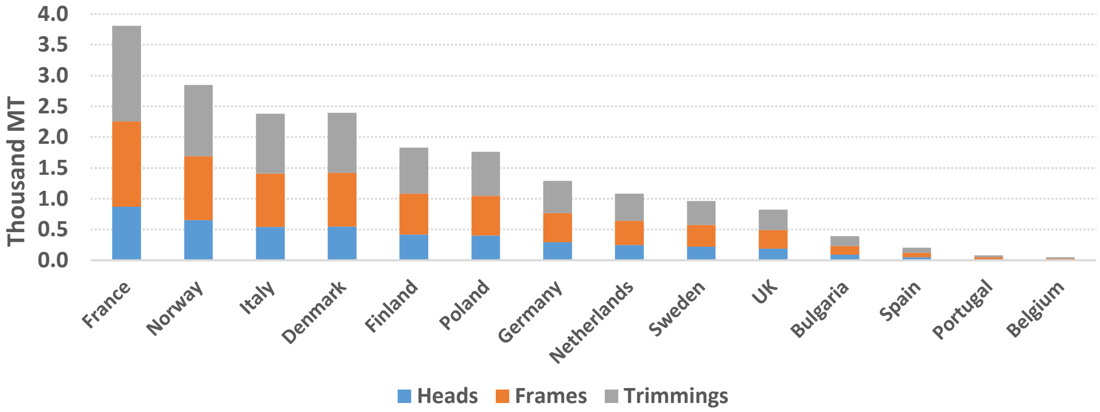


Figure 4.12: Potential flesh yield from rainbow trout processing by-products.

European seabass and gilthead seabream

Limited potential for extra flesh production from European seabass is due to low secondary processing in Europe (Figure 4.13). The biggest potential, according to our model is in Northern European countries that secondary process imported HOG. However, the volumes are very small compared to Atlantic salmon. Further processing in Southern European exporting countries would increase the available by-products for flesh recovery, but whether this would result in more of the fish being consumed over that available from whole fish, is open to debate. A similar story is found with gilthead seabream (Figure 4.14) which has similar processing patterns to European seabass but with Germany being a more important importer than for European seabass.

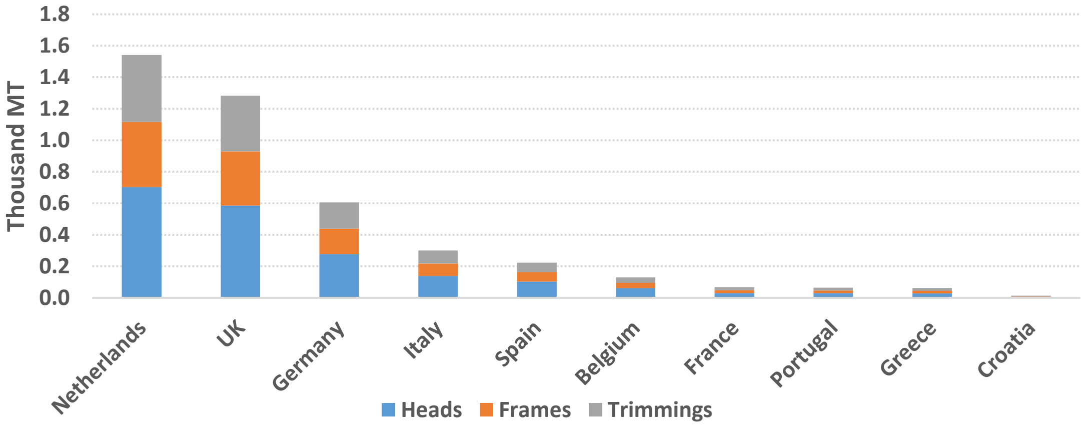


Figure 4.13: Potential flesh yield from European seabass production and processing.

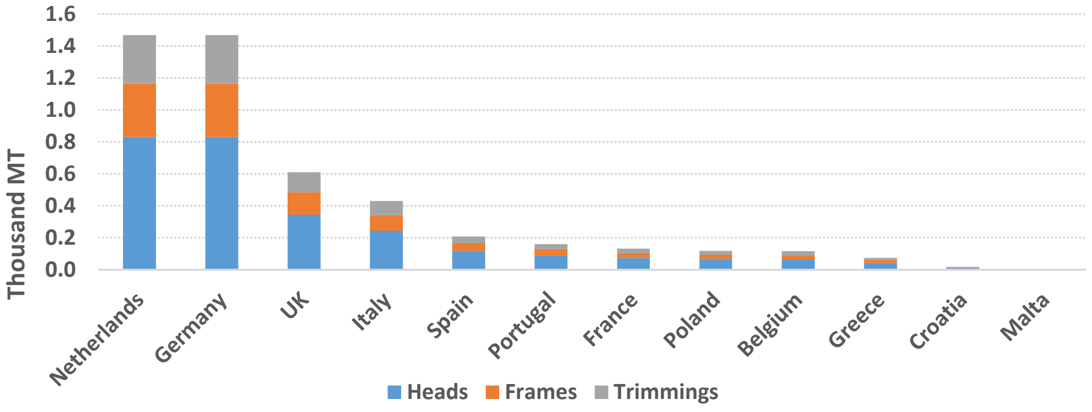


Figure 4.14: Potential flesh yield from gilthead seabream processing by-product.

Common carp

Common carp is not heavily processed in Europe and consequently there are few available by-products for flesh recover (Figure 4.15). Low by-product volumes and comparatively lower perceived quality than some other species is unlikely to make recovery feasible with current processing activities. However, sale of whole carp provides the opportunity for households to maximise edible yields. Spanish carp by-products are due to their small export volumes as explained above.

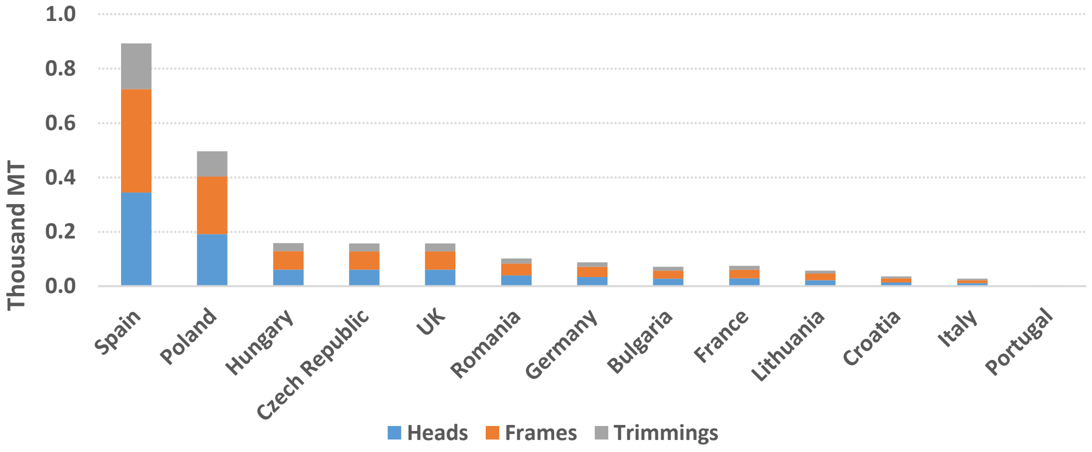


Figure 4.15: Potential flesh yield from common carp processing by-product.

Turbot

As a niche species, the availability of turbot by-products is very low (Figure 4.16). Most potential is from Spain, who could produce a few hundred tonnes of recovered flesh. It is likely that with such low volumes, more value could be obtained rendering into marine ingredients, perhaps mixed with other species.

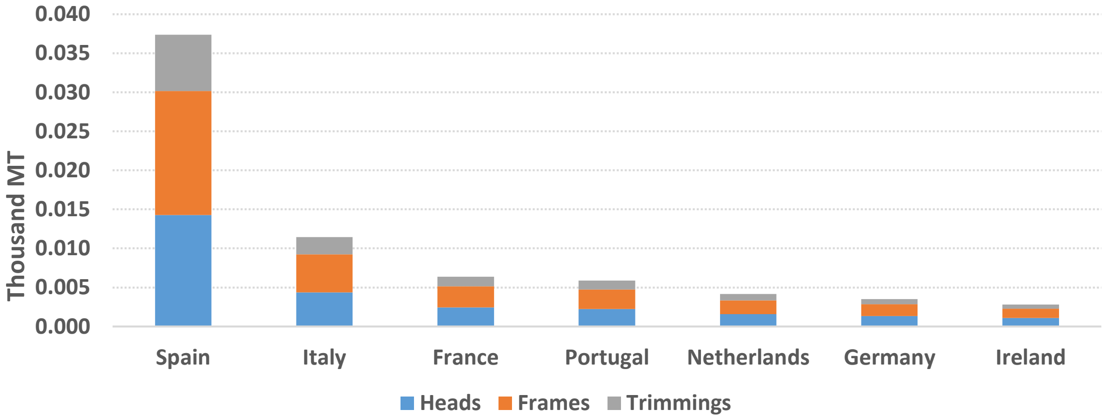


Figure 4.16: Potential flesh yield from turbot processing by-product.

Fish protein hydrolysates and peptones

Fish protein hydrolysate (FPH), a mixture of low molecular weight protein and peptides can readily be made from fish by-products. This process is described in the flowchart (Appendix A2.7), starting first with crushing of the by-products followed by a range of chemical and enzymatic treatments with heat and pressure. Liquid hydrolysates, oil, and wet/dry bones (which are considered waste) are filtered and separated by centrifuge, followed by additional treatments, such as filtration, vacuum-evaporation and spray drying to give concentrated and dry FPH.

Peptones are soluble proteins formed in the early stage of protein hydrolysis. The by-products are ground and then may be subjected to two processes to produce different types of peptones; thermal or FPH peptone (Appendix A2.8). For thermal peptone, water is added to the by-product mix and subjected to autoclaving, filtration, and centrifugation, resulting in solids, bones, oil, and the thermal peptone (TP). The second process includes the adding of water and alcalase followed by filtration, resulting in bones and raw hydrolysate. The latter is then centrifuged resulting in the separation of oil and pre-peptone which is autoclaved and centrifuged to produce FPH peptone, which may then be combined with the thermal peptone originating from the first process.

FPH and peptones from Atlantic salmon by-products

Results show high volumes of FPH, peptone and oil can be produced from available by-products in Poland, Norway, and Denmark (Figure 4.17, 4.18 and 4.19). Poland shows the largest potential volume for marine ingredients from secondary processing by-products. High volumes of FO and dry peptones produced from viscera from primary processing in Norway and the UK could be obtained. As an indication, the oil that could be produced from peptone manufacturing, is around 10% of the around 160 thousand tonnes of high-quality FO used by the Norwegian salmon industry within its feed supply in 2016 (Aas, Ytrestøyl and Åsgård, 2019a). Although the quality of oil from by-products is likely to be lower and there may be resistance to its use in the salmon industry because of fears around intra-species feeding, it may be used in other industries and increase the overall supply of FO available. The yield of oil from heads, trimmings and frames is reasonably similar between peptone and hydrolysate production.

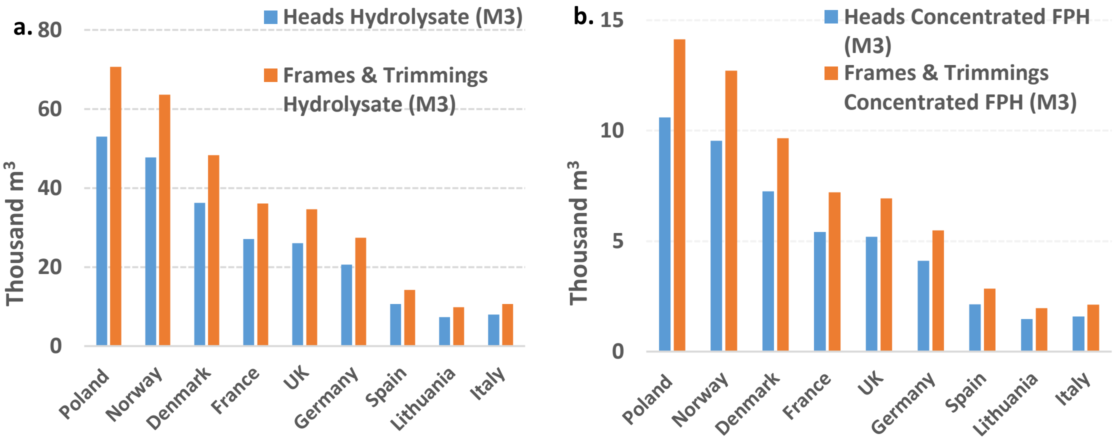


Figure 4.17: a) Liquid hydrolysate b) concentrated hydrolysate production from Atlantic salmon heads, frames, and trimmings.

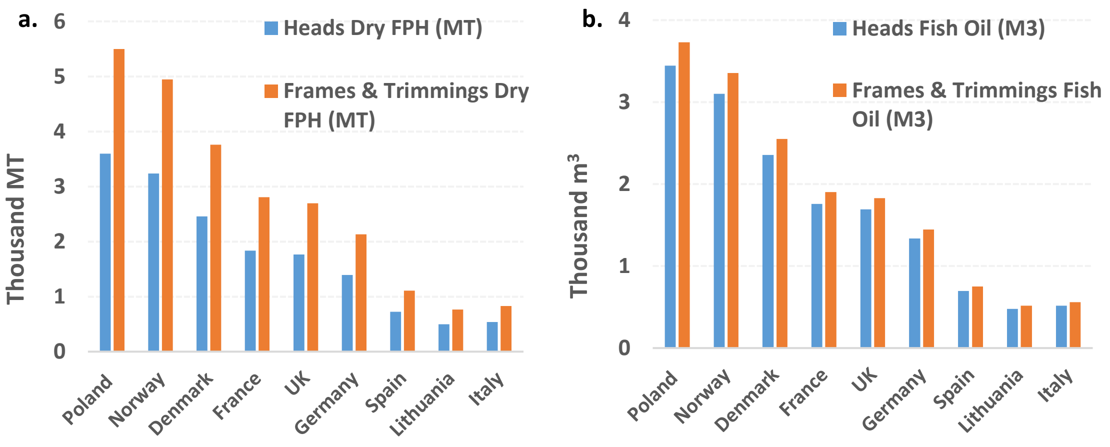


Figure 4.18: a) Dry FPH b) FO from heads, frames & trimmings from Atlantic salmon.

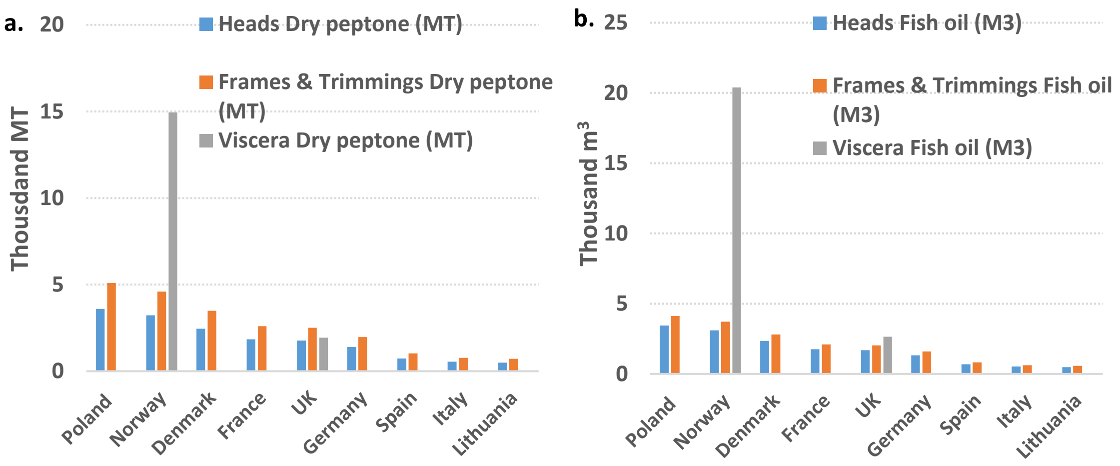


Figure 4.19: a) Peptones and b) FO from Atlantic salmon heads, frames & trimmings, and viscera.

FPH, oil and peptones from rainbow trout by-products

France, Norway, and Italy, who produced and processed large quantities of rainbow trout have the largest potential for producing FPH from trout heads, frames and trimmings but is small compared to Atlantic salmon (Figure 4.20, 4.21 and 4.22). Modest quantities of oil may be produced from the viscera of producing countries where primary processing occurs.

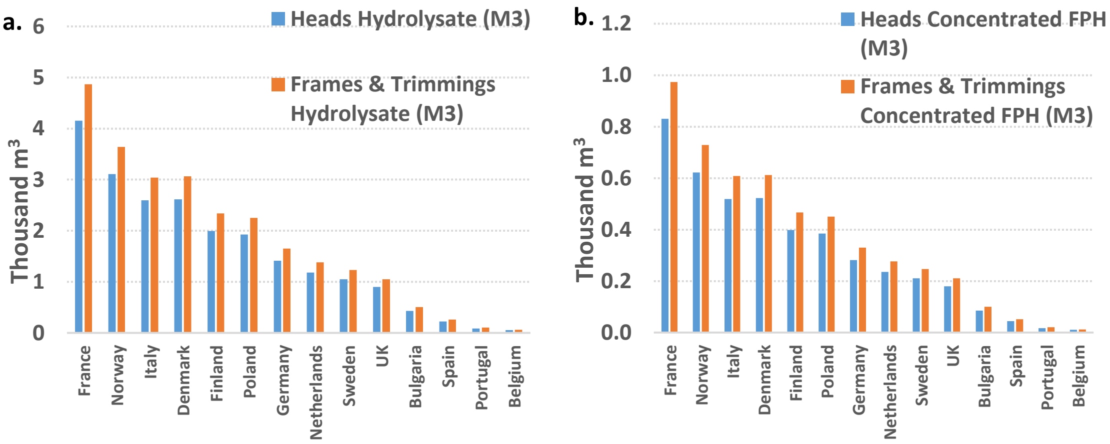


Figure 4.20: a) Liquid hydrolysate b) concentrated hydrolysate production from Atlantic salmon heads, frames, and trimmings.

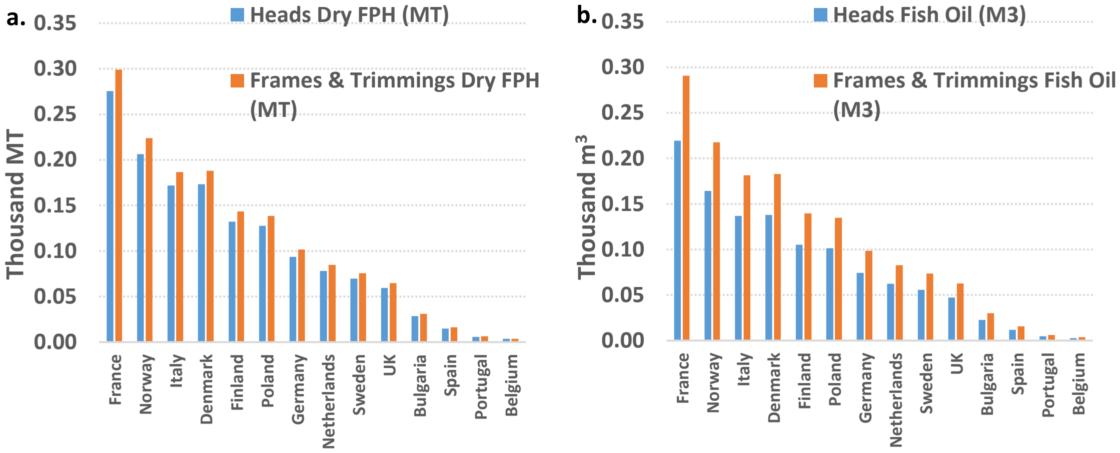


Figure 4.21: a) Dry FPH b) FO from heads, frames & trimmings from rainbow trout heads, frames, and trimmings FPH production.

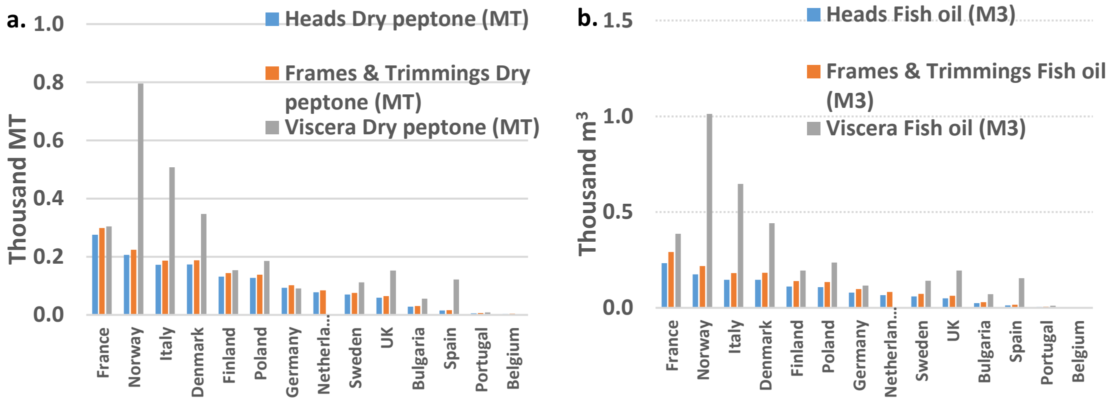


Figure 4.22: a) Peptones and b) FO from rainbow trout heads, frames & trimmings, and viscera.

Oil and peptones from European seabass and gilthead seabream by-products

Modest volumes of FO and dry peptones could potentially be produced from European seabass and gilthead seabream viscera in the major producing countries, such as Greece and Spain (Figure 4.23 and 4.24). Importing countries also show potential to produce dry peptones from heads, frames, and trimmings but the volumes are quite low.

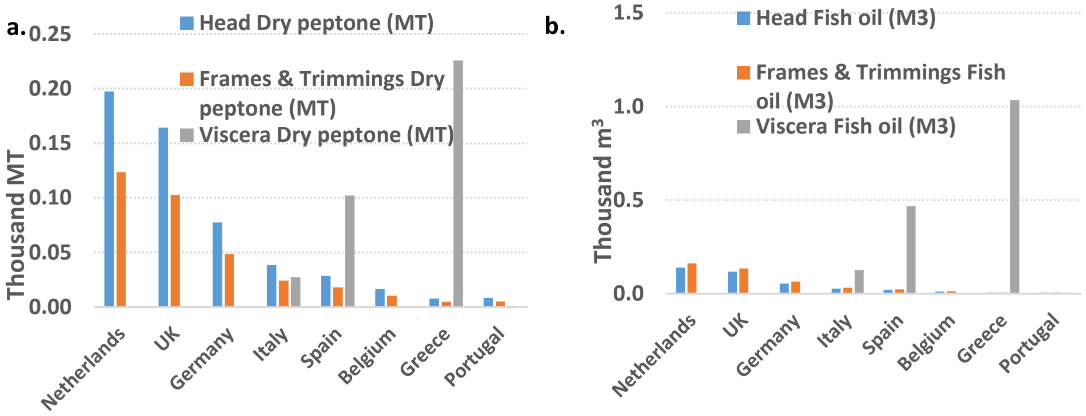


Figure 4.23: a) Peptones and b) FO from European seabass heads, frames & trimmings, and viscera.

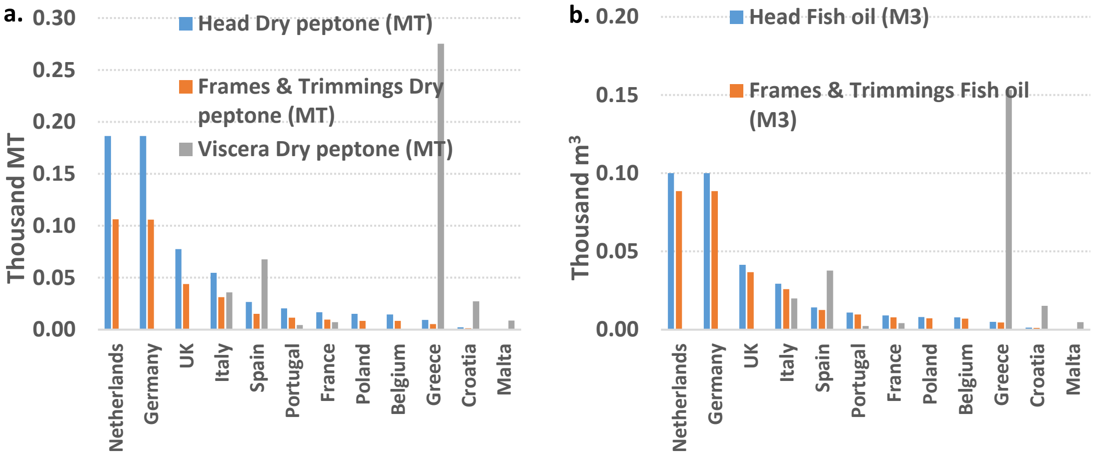


Figure 4.24: a) Peptones and b) FO from gilthead seabream heads, frames & trimmings, and viscera.

FPH, oil and peptones from turbot by-products

Highest potential for FPH is in Spain, which produces and process, as well as imports, turbot (Figure 4.25, 4.26 and 4.27). Volumes are low compared to other species because of the low volumes of by-product available.

Low volumes of FO and dry peptones could be produced from turbot viscera in Spain as the largest producer and processor of turbot. Importing countries may also produce peptones from secondary processing by-products. The volumes of peptones obtainable from heads, trimmings and frames are relatively similar. However, FO yields (Appendix A2.8) differ significantly between different by-products.

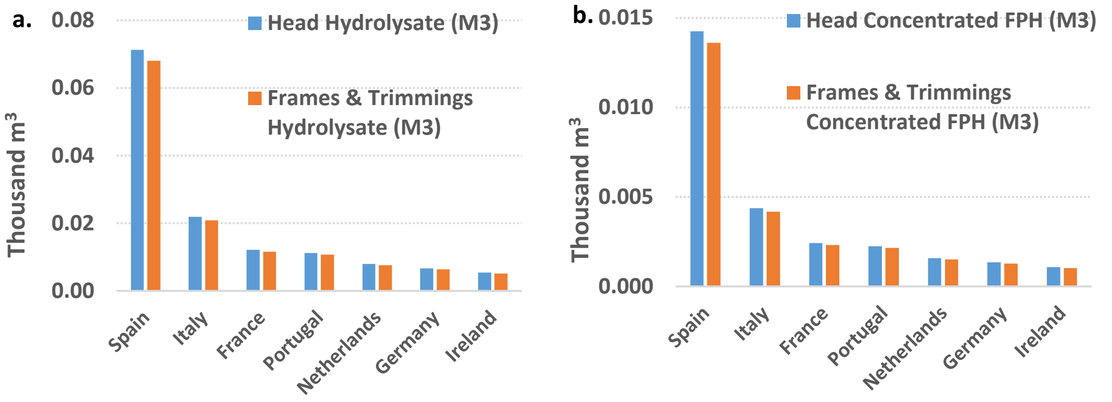


Figure 4.25: a) Liquid hydrolysate b) concentrated hydrolysate production from turbot heads, frames, and trimmings.

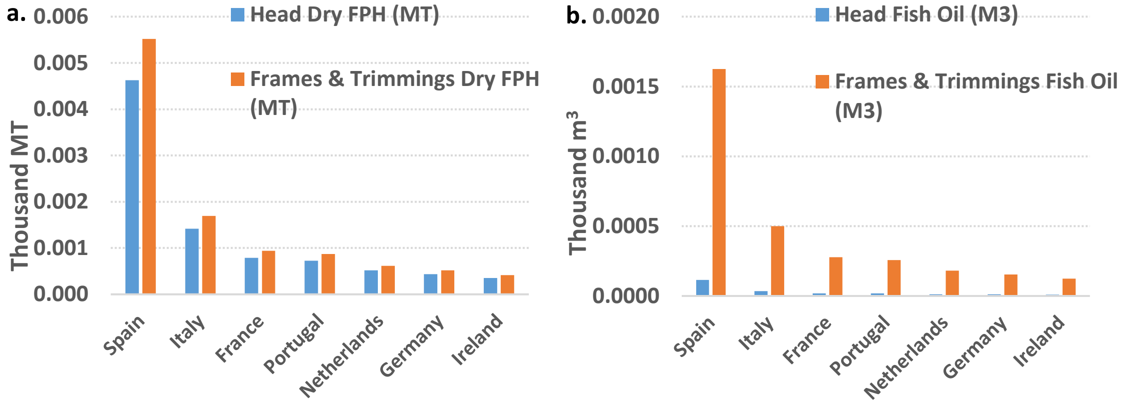


Figure 4.26: a) Dry FPH b) FO from heads, frames & trimmings from turbot heads, frames, and trimmings FPH production.

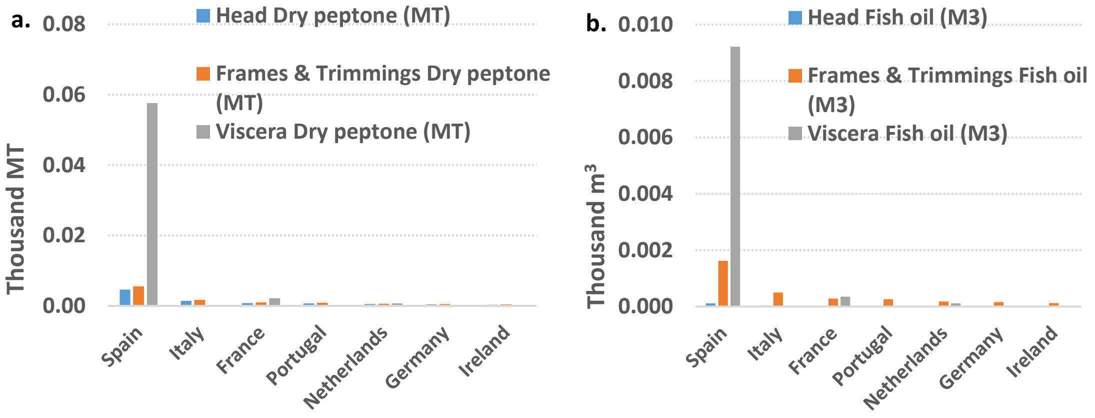


Figure 4.27: a) Peptones and b) FO from turbot heads, frames & trimmings, and viscera.

Collagen and gelatine extraction from Atlantic salmon skins

Marine collagen is of growing interest although from Figure 4.28a, European aquaculture looks less likely to make an impact on the world market. Fish collagens are of interest because of their solubility properties, which are attractive for cosmetics industries. Note that although collagen and gelatine extraction were investigated by IIM-CSIC, there are currently no turbot skins available from processing activities, according to our trade balance. Therefore, there is no projected volumes of turbot collagen and gelatine available.

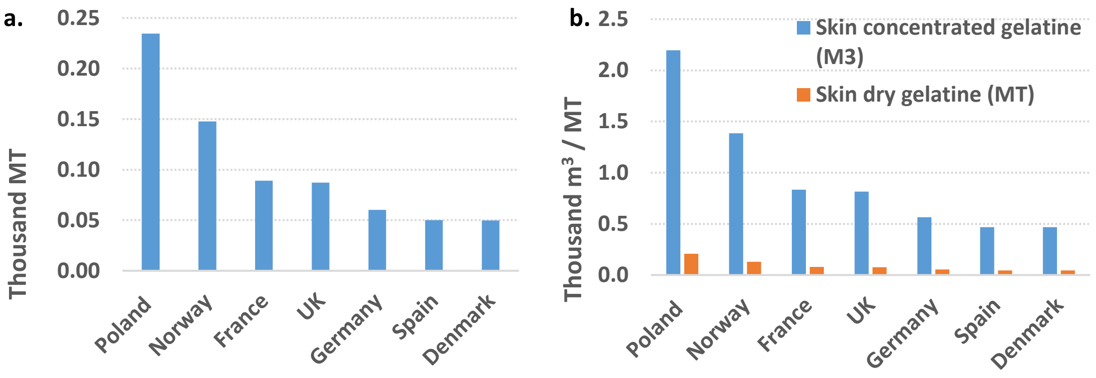


Figure 4.28: a) Collagen and b) gelatines from Atlantic salmon skins.

4.3.2 Nutritional characterisation of aquaculture processing by-product in Europe

The by-product proportions, edible (flesh) yields), proximate composition and fatty acid profiles of the various by-products of the European species are described below. All results are presented on a wet weight (ww) basis. Absolute values and standard deviations are available in the Supplementary Information (*Nutritional Composition of the By-products*), organized by species in *Table S1 to S5* (Malcorps *et al.*, 2021c). Not included in these tables in the supplementary information are the fillet yields, which have been included in Figure 4.29 and Table 4.12 within the main text.

By-product proportions and edible yield

Fillet yield, and hence the by-product proportion, differs between species (Figure 4.29). The results indicate that Atlantic salmon has the largest fillet yield of the species studied at almost 56.2 ± 1.6% of the total body weight, compared to turbot fillets which were the lowest at 30.5 ± 1.7% of bodyweight. Gilthead seabream showed the largest head proportion at 27.6%, while turbot had the highest share of trimmings and skin at almost 13.5% and 14.3% of the total bodyweight, respectively. Viscera proportions ranged between 5.8% (turbot) and 13.5% (common carp).

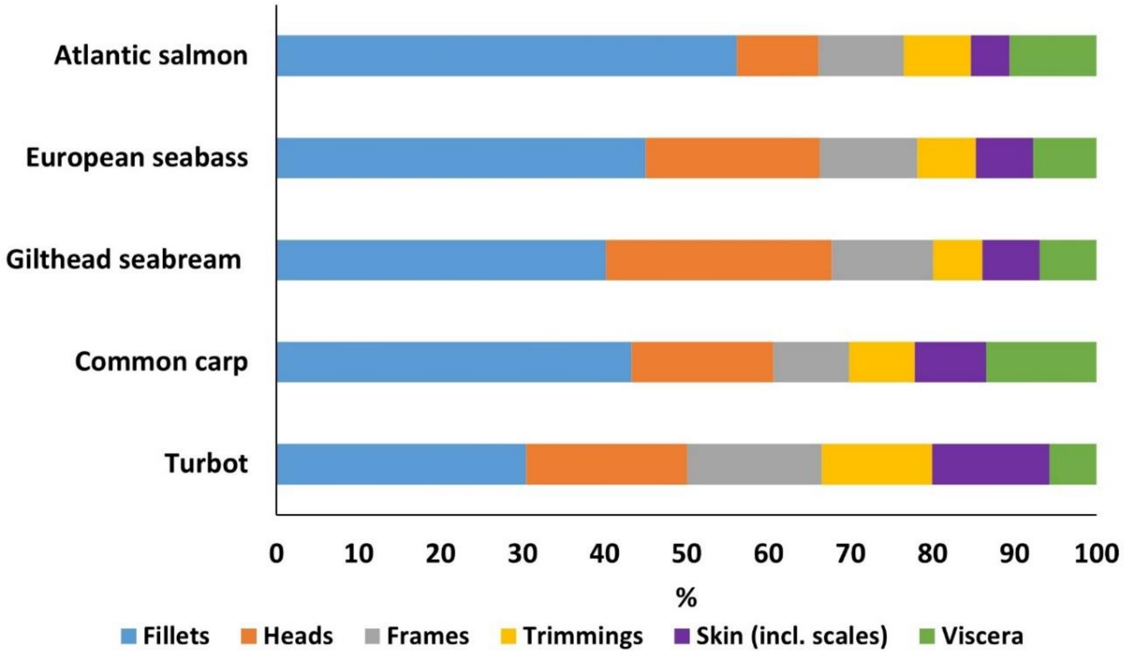


Figure 4.29: Proportion (%) of different processing fractions for five important European aquaculture species.

Extraction of edible components (Table 4.12, Figure 4.30a) from each of the by-product fractions, demonstrated that the potential total edible yield exceeded 70.0% of harvested yield for four-fifths of the species studied, compared to 56.2% or less from the fillet alone. Edible yields from heads showed a low variability, 37.2% (Atlantic salmon) to 48.9% (Gilthead seabream), compared to frames ranging from 41.8% (European seabass) to 90.0% (common carp) and trimmings 27.3% (turbot) to 83.9% (Gilthead seabream). Overall, total edible yields were the highest for Atlantic salmon at up to 77.1%, while turbot was at the low end with 63.7%. However, turbot showed the highest increase in total edible yield from by-products by up to 33.3%, while Atlantic salmon showed the lowest by up to 20.9% (Table 4.12).

Table 4.12: By-product fractions and associated edible yield and total edible yield of the 5 European aquaculture species.

Species / fraction		BP fraction of whole %	Edible yield %	By-product fraction of whole %	Edible by-products as % of whole fish	Total edible yield %
Atlantic salmon	**Heads**	9.9	37.2	43.8	20.9	77.1
	Frames	10.4	56.7			
	Trimmings	8.2	81.0			
	Skin (incl. scales)	4.7	100			
	Viscera	10.6	0			
	Fillet	56.2	100			
European seabass	**Heads**	21.2	40.6	55.0	25.8	70.8
	Frames	11.9	41.8			
	Trimmings	7.1	73.6			
	Skin (incl. scales)	7.0	100			
	Viscera	7.7	0			
	Fillet	45.0	100			
Gilthead seabream	**Heads**	27.6	48.9	59.9	31.2	71.3
	Frames	12.4	46.1			
	Trimmings	6.0	83.9			
	Skin (incl. scales)	7.0	100			
	Viscera	6.9	0			
	Fillet	40.1	100			
Common carp	**Heads**	17.3	43.5	56.8	28.3	71.5
	Frames	9.3	90.0			
	Trimmings	8.0	46.0			
	Skin (incl. scales)	8.7	100			
	Viscera	13.5	0			
	Fillet	43.2	100			
Turbot	**Heads**	19.6	37.0	69.6	33.3	63.7
	Frames	16.4	49.4			
	Trimmings	13.5	27.3			
	Skin (incl. scales)	14.3	100			
	Viscera	5.8	0			
	Fillet	30.4	100			

Proximate analysis

All results are presented on a ww basis (Figure 4.30), and available in *Table S1 to S5*. Moisture variability (Figure 4.30b) between species was very low in heads, frames, skin, and trimmings, while viscera showed high variability ranging from 31.9% for European seabass to 70.9% for turbot. Ash content (Figure 4.30c) was very low between 1.0 to 2.0% for skin and viscera for all species, but more variable among species for trimmings between 2.2-6.9%, heads between 5.0-10.1% and frames between 1.9-12.4%. Ash content was highest for European seabass frames at 12.4%. Crude protein (Figure 4.30d) values ranges were as follows; for heads between 13.1-20.2%, frames between 16.8-19.4% and viscera between 11.1-17.2%, but was constant within the skin between species at around 20%, with turbot skin at the high end at 23.4%. Trimmings exhibited similar upper values with more variability between species, with the lowest value of 15% crude protein for common carp. Total lipid content (Figure 4.30e) variability was low for frames, but high for heads, skin, viscera, and trimmings between the species. Atlantic salmon demonstrated high lipid content in heads at 21.5%, frames at 17.2% and trimmings at 26.4%. However, lipid levels in European seabass viscera at 39.3%, and common carp skin stood out at 37.4%. Highest variability was observed for European seabass viscera at 21.9% (Figure 4.30e).

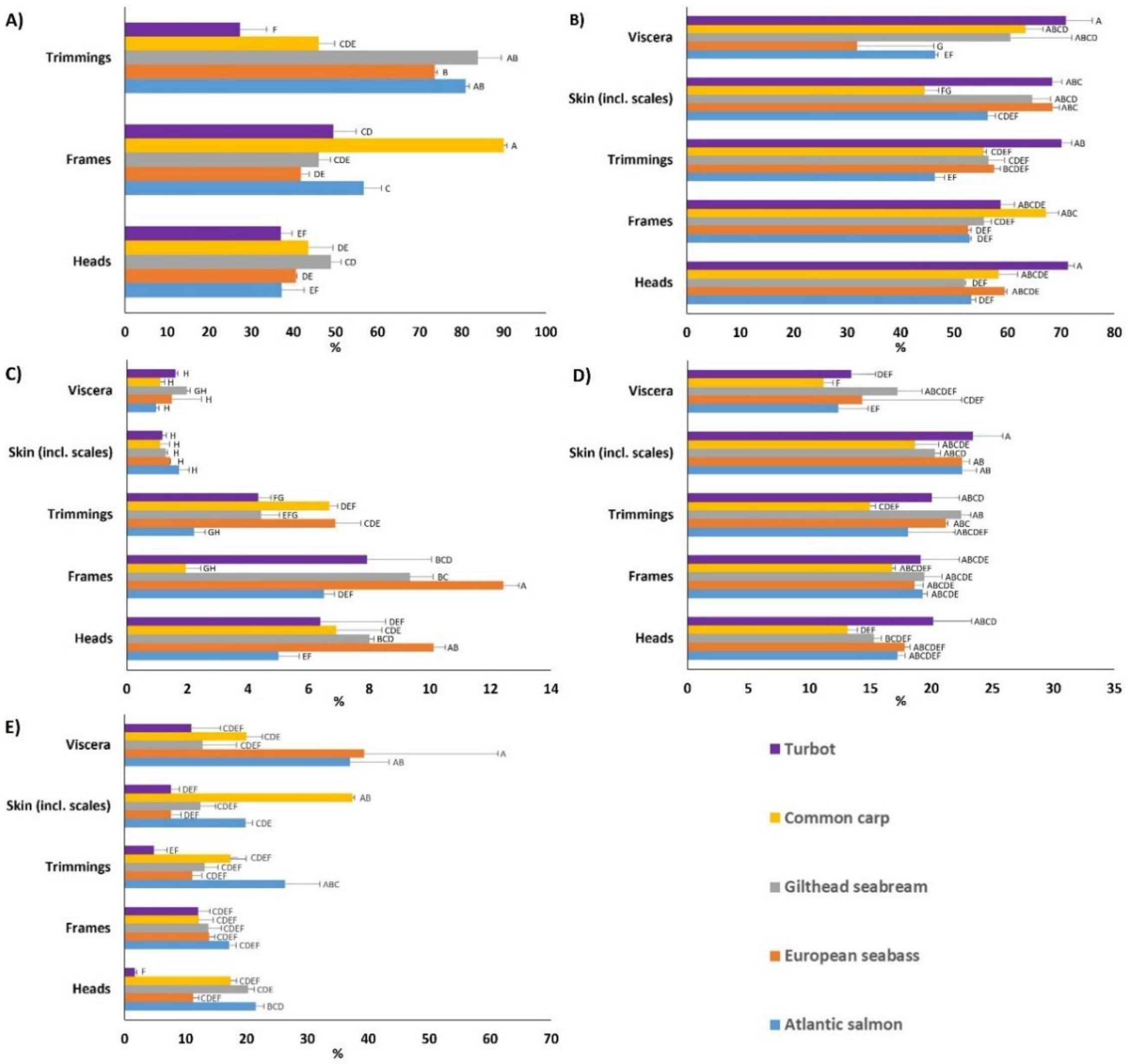


Figure 4.30: A) Edible yield and proximate composition (% of wet weight) B) moisture, C) ash, D) crude protein, E) and total lipid of the various by-products for the European aquaculture species. Means that do not share letter(s) (A-H) are significantly different.

EPA and DHA content

By species, the highest EPA+DHA (g. 100 g^{-1} ww) values, were observed for Atlantic salmon in heads at 1.53 g. 100 g^{-1}, trimmings at 1.74 g. 100 g^{-1} and skin at 1.21 g. 100 g^{-1} (Figure 4.31, Table S1 to S5). However, for by-products, Atlantic salmon viscera showed the second largest EPA+DHA content at 1.10 g. 100 g^{-1}, after European seabass at 1.99 g. 100 g^{-1}, and in salmon frames at 1.18 g. 100 g^{-1}, after turbot at 1.32 g. 100 g^{-1}.Turbot showed a relatively high EPA+DHA content in frames at 1.32 g. 100 g^{-1}, skin at 0.85 g. 100 g^{-1} and viscera at 0.83 g. 100 g^{-1}, while heads and trimmings showed significant lower values compared to most species. The lowest values were observed for common carp, the only freshwater species analysed in this study.

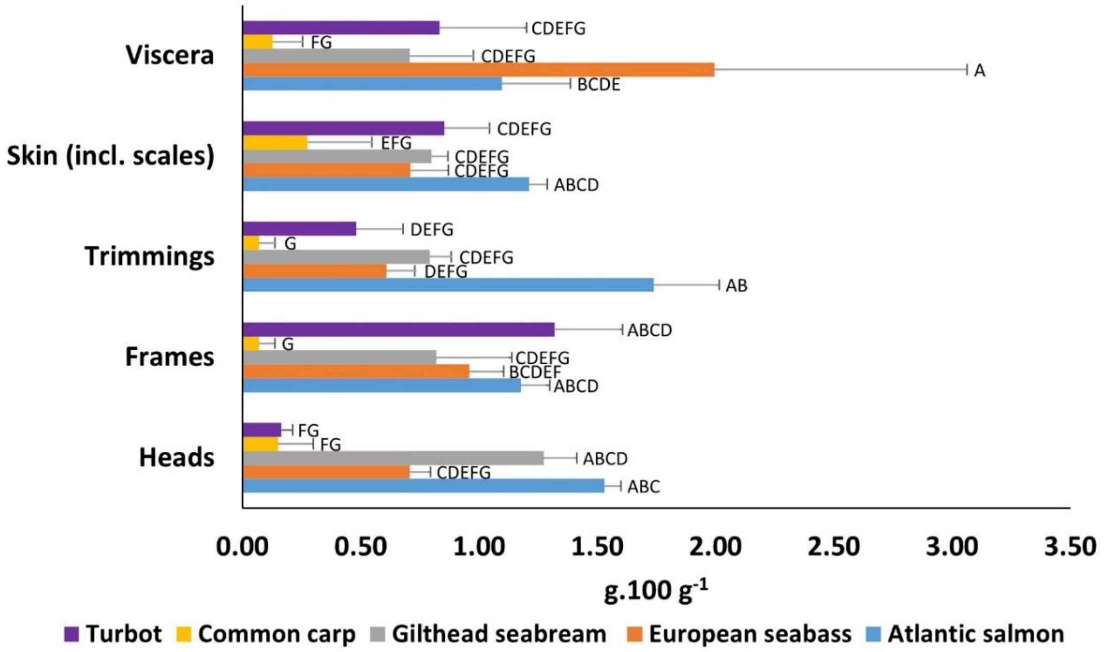


Figure 4.31: Total EPA+DHA content (g.100 g^{-1}) of wet weight by-products from European aquaculture species. Means that do not share letter(s) (A-G) are significantly different.

Fatty acid profiles

The relative proportion of the fatty acid classes is related to the total lipid content (Figure 4.32). There are similarities across the different species and their derived by-products, except for common carp (Figure 4.32, Table S1 to S5). Total saturated FAs is variable across the by-products and species but are relatively higher in the viscera of Atlantic salmon at 4.44 g. 100 g^{-1} (of ww sample), European seabass at 7.02 g. 100 g^{-1} and common carp at 4.07 g. 100 g^{-1}. Additionally, common carp skin also showed relatively high absolute values for total saturated FA at 7.92 g. 100 g^{-1}. Total n-6 PUFA showed variability and has relatively higher values for viscera of Atlantic salmon at 4.05 g. 100 g^{-1} and European seabass at 5.31 g. 100 g^{-1} and trimmings of Atlantic salmon at 3.83 g. 100 g^{-1}.

The highest inclusion of n-3 PUFA can be found in the by-products of Atlantic salmon, ranging between 3.88 g. 100 g^{-1} for trimmings and 2.47 g. 100 g^{-1} for frames. European seabass viscera also showed a high value at 3.40 g. 100 g^{-1}. The content of EPA+DHA as a percentage of total n-3 PUFAs showed variability averaged across heads, frames, trimmings, skin (incl. scales) and viscera of 44.6% (±4.5) for salmon, 64.1% (±3.8) for European seabass, 58.1% (±0.8) for gilthead seabream and 61.7% (±5.8) for turbot. However, common carp showed lower EPA+DHA values across by-products with an average of 29.8% (±5.2) as a percentage of total n-3 PUFAs.

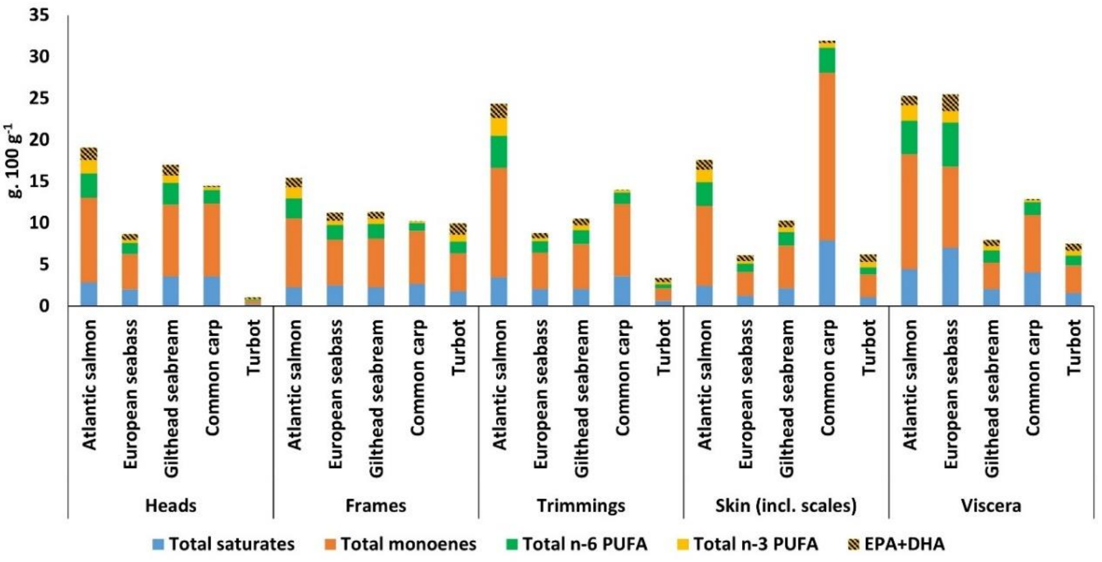


Figure 4.32: Fatty acids group content in g.100 g^{-1} of wet weight sample, excluding 16:2, 16:3 and 16:4. The totals of the fatty acid groups could slightly differ from the total lipids (Figure 4.31), as means of fatty acid groups were used.

4.3.3 Case study common carp: value-added through strategic fish processing

The carp sector is characterised by traditional farming in large ponds and with a relatively small processing sector, as most carp is sold live during the Christmas period (Raftowicz and Le Gallic, 2019). However, in recent years, fish welfare concerns and opportunities to add value to carp (by-) products are driving an interest towards increased processing. Nevertheless, the potential to increase the economic value of the industry is relatively unknown.

There are different carp products available on the market (Table 4.11) across a range of prices. Traditionally, by-products originating from the processing of these products are currently discarded. It is therefore assumed that there is underutilised potential, which could be explored by creating processing scenarios.

The sale of whole/live carp (S1) showed the highest production output (1 MT whole fish). However, it is then assumed that the whole fish is utilised, including by-products, which is often not the case as these by-products accumulate at the household level. In the case of sc6-10, all co-products are being utilised on a processor level (Figure 4.33). The production forms (S2-5) are assumed to discard most by-products and showed therefore a lower production output.

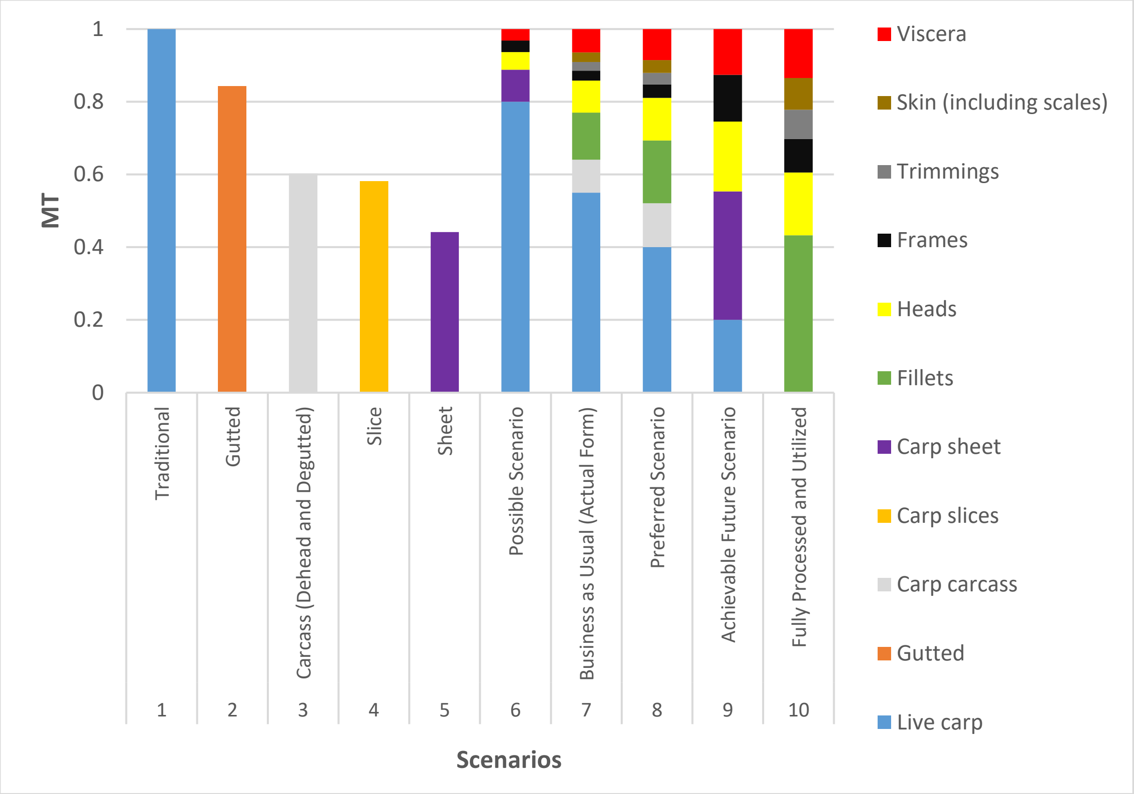


Figure 4.33: Co-product output per MT from common carp aquaculture production in Poland.

The yields and price per commodity are variable (Table 4.11), which affects the total economic value output. Nevertheless, this showed a relatively similar trend compared to the co-product output (Figure 4.33). Interestingly, the high yield of live carp (100%) in combination with a relatively high kilo price indicates incentives to sell it in the traditional product form. Similar value could be obtained by S6 (combination of live sales and processed: 80% live + 20% sheets incl. by-products). Consequently, when the use of by-products increased, the economic value output increased with it, as seen from sc7-10, in which scenario 10 is fully processed. However, it is important to consider that in all these scenarios the “market price” was applied (Table 4.11), which does not include the variability of prices that could be obtained depending on the utilisation pathways, as discussed in Figure 4.35.

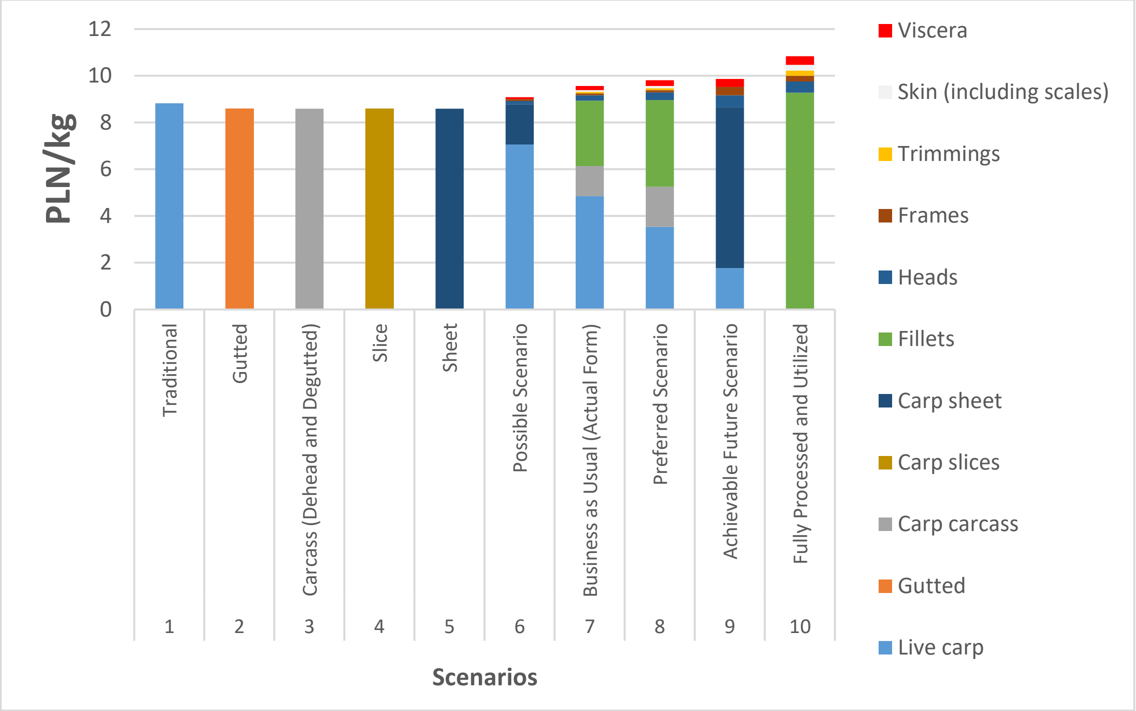


Figure 4.34: Potential value output (PLN/kg) on a kilogram basis on a co-product resolution.

Result indicates a variability in economic value output, in which by-products application in food and industrial use show the highest potential (Figure 4.35). The least attractive option is associated with dumping by-products on the landfill or incineration, as this has associated with costs. This accounts specifically for S9 (20% live + 80% sheets incl. by-products) and S10 (40% Fillets + 60% by-products, such as heads, frames, trimmings, skin, and viscera).

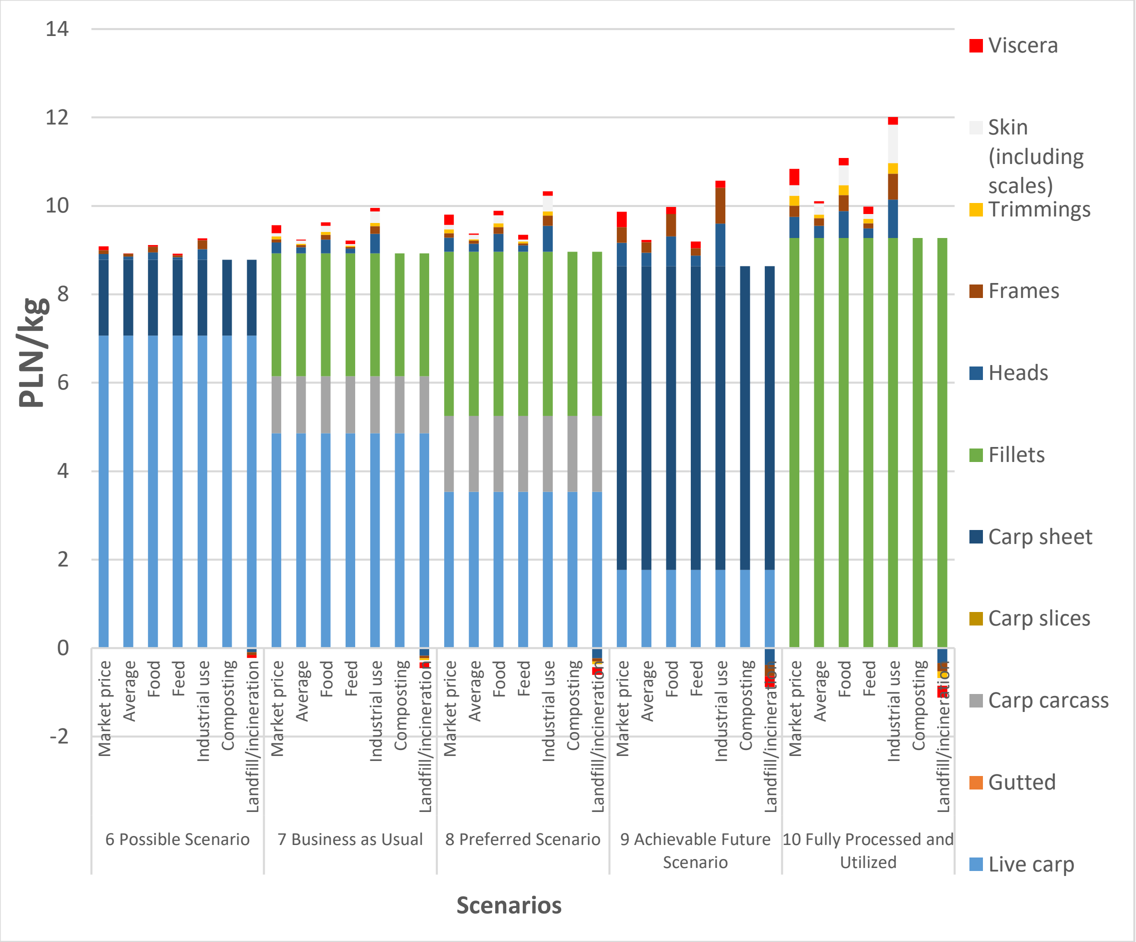


Figure 4.35: Potential economic value output on a kilogram basis on a co-product resolution (PLN/kg). This Figure is an extension of Figure 4.34, including different strategic utilisation pathways in scenario 6-10.

4.4 Discussion

Improved utilisation of the "whole fish" is a key component of the sustainable intensification of seafood value chains (Little *et al.*, 2018), and through reducing waste supporting progress towards ensuring sustainable consumption and production patterns (UN, 2020). The by-product analysis showed the largest volumes of by-products available from Atlantic salmon in Norway followed up by Poland, while interestingly most flesh could be obtained from the heads, frames, and trimmings in Poland, as a result of the large-scale secondary processing of Norwegian salmon. On a by-product level, the potential total edible yields showed a range of 64% to 77% for turbot and Atlantic salmon, respectively, while fillet yields between these species range significantly between 30% and 56%, respectively. Total edible yields could potentially double compared to fillet only depending on the type of species, and total edible yield is much more similar between species than from fillet alone (Table 4.12). A focus on the available volumes and nutritional value of the by-products is required to get the best out of these high edible yields. In the following sections the volumes and nutritional value are discussed in relation to available literature and the food recovery hierarchy for fish by-products (Stevens *et al.*, 2018; USEPA, 2020), followed up by challenges associated with the strategic utilisation of by-products, recommended policies and future research perspectives.

Volume characterisation of the by-products

The aquaculture industry fulfils an important role to meet growing demands for seafood. However, according to Jackson and Newton (2016), there are approx. 0.6 million MT of unutilised seafood by-products (from capture fisheries and aquaculture) across Europe. Redirecting by-products for direct human consumption or as feed ingredient would increase the efficiency of the industry by cutting waste and providing more raw materials across the food industry, which could help bridge the protein gap according to circular economy principles.

The results indicate that there are substantial volumes of edible yield from by-products, particularly Atlantic salmon which could be directed to human consumption. For other species, the full edible yields may be obtained from consumption of whole fish or from separation from processing by-products. However, abstracting those edible portions may be difficult, mechanically from by-products or in-home consumption scenarios, and as yet, has not been fully assessed. There are large Atlantic salmon by-product volumes, especially in Norway, because of large production volumes in combination with efficient primary processing, resulting in e.g., large volumes of FO from viscera. Secondary processing of salmon is more geographically dispersed, especially to Eastern Europe (e.g., Poland). Consequently, most potential for by-product derived feed ingredients, such as hydrolysate, peptones and FO are not always near the production centres and dispersed volumes of by-products may make value addition less attractive. Volumes of rainbow trout, European seabass and gilthead seabream are less than for salmon because production and level of processing is lower, but there are some similarities in that producing countries are not necessarily the centres for secondary processing. However, processors (e.g., Greece) could produce large volumes of products from viscera, particularly FO.

Production volumes play an important role in the availability of by-products. However, by-product availability could be increased by intensifying the processing stage. The results indicate that Atlantic salmon and rainbow trout are the most advanced species in terms of processing intensity. By-product availability for European seabass, gilthead seabream, common carp and turbot are low because of local preference for consuming these species unprocessed, while for common carp and turbot production volumes are also relatively low. Nevertheless, production volumes of European seabass and gilthead seabream are high while the trade balance results also indicate a lack of secondary processing, resulting in missed opportunities regarding the utilisation of heads, frames, and trimmings. This lack of processing is also the case for turbot in which the derived by-products show interesting nutritional characteristics for a variety of applications according to the lab analysis. The lack of full secondary processing is also applicable to the Italian rainbow trout value chain, according to the trade balance. Italian respondents indicate a lack of interest towards fresh products and low prices for trout. In response farmers are increasingly processing and diversifying their products (hamburgers, smoked fish, fish skewers) (Iandoli and Trincanato, 2007). However, this opportunity could be further exploited by further diversifying products and producing ready to eat products, while utilising some by-products into feed, cosmetics, and nutraceuticals, as indicated by respondents. Overall, Southern European aquaculture shows potential to increase the economic value of the aquaculture sector by means of full (primary and secondary) processing. Nevertheless, this imposes other challenges, such as consumption preferences, which can vary greatly across Europe from whole fish compared to various processed forms of different species (EUMOFA, 2017).

Nutritional characteristics of the by-products

Most of the nutritional differences found in the by-product samples between this thesis and assessed literature could be explained by age, sex, environmental factors and nutrient intake (Huss, 1995). The latter could explain the high variability for most nutritional parameters within viscera for all European species, as viscera is often the area where most lipid deposition occurs especially if feed is not balanced, or fish is overfed. In addition, comparative efficiency of the investigators in terms of obtaining flesh from bones and heads, differences in origin (aquaculture vs fisheries), intensity (intensive vs extensive) production systems (land vs cage culture) harvest size and weight. Additionally, processing practices, such as the extent of bone removal, can explain differences in by-products fractions. Homogenisation strategies, i.e., if whole fish are homogenised or analysis is made on tissue samples can result in overlooking the retention of nutrients in certain by-product fractions. For example one study from Aas *et al.* (2019a) found that salmon retained only 37% of EPA+DHA from which 23% was retained in the fillets and the rest in by-products, explained by a disproportionate accumulation of fat in the viscera relative to the muscle (Aas, Ytrestøyl and Åsgård, 2019b).

The findings for Atlantic salmon when compared to that of Stevens *et al.* (2018), found significant differences in edible yield for heads (37% and 25%), frames (57% and 32%) and trimmings (81% and 68%, trimmings and belly flaps combined), respectively, despite lab conditions and methods being similar. The higher edible yield in this analysis is likely to affect the nutritional composition of the homogenised sample, explaining some of the nutritional differences. The differences in EPA+DHA content (Table S1) could be explained by the nutritional content of the feed reflected in the fatty acid content of the harvested fish (Sprague, Dick and Tocher, 2016). Marine ingredient inclusion in Norwegian salmon feed has declined drastically in the last three decades (Ytrestøyl, Aas and Åsgård, 2015) in comparison to fish farmed in Scotland (Shepherd, Monroig and Tocher., 2017).

The findings for European seabass from Spain (Table S2) were relatively similar with the values for seabass sourced from an intensive and extensive farm in Italy, and their derived homogenised by-products (Messina *et al.*, 2013). Difference in processing cuts could also explain the higher skin lipid content (17%) in the study of Munekata *et al.* (2020) from seabass homogenised by-products sourced at a Spanish market, as this homogenised skin sample (8%) had flesh attached to it.

Gilthead seabream by-products (Table S3) had similar nutritional values compared to the study of Pateiro *et al.* (2020), who used fishery derived male seabream purchased from a local market in Spain, and their derived by-products. However, the head proportion from this study was 28% ± 0.5%, while Pateiro *et al.* (2020) reported 21%. Additionally, skin, moisture, total lipid and DHA content differed with Pateiro *et al.* (2020) for reasons already stated.

Polish common carp aquaculture is characterized by “natural” extensive production systems (Raftowicz and Le Gallic, 2019), and is the only freshwater species assessed in this study. Lipid content of homogenised by-product samples was higher, while EPA+DHA was lower (Table S4), compared to the muscle tissue samples from three (intensive, low-intensive, and semi-extensive) production systems (Kłobukowski *et al.*, 2018). While sample difference could explain the differences, production systems and their associated feed ingredient use could impact the fatty acid profile according to the study of Kłobukowski *et al.* (2018). EPA and DHA are more common in the marine food chain, but some freshwater species could also serve as a source of EPA and DHA. However, in general the freshwater food chain contains higher levels of linoleic acid (LOA) (C18:2 n-6) and alpha-linolenic acid (ALA) (C18:3 n-3) (Strobel, Jahreis and Kuhnt, 2012). Nevertheless, common carp requires n-3 and n-6 fatty acids in their diet (Takeuchi, Satoh and Kiron, 2002; Glencross, 2009), which can be manipulated through enriched feed (Eljasik *et al.*, 2020).

The nutritional results for farmed turbot are relatively similar to other literature with the exception of lipid and ash results, which are much higher for frames, skin and viscera (Table S5) compared to the values shown in Martinez *et al.* (2010). While the DHA results are relatively similar to Martinez *et al.* (2010), the EPA values are significantly lower. Differences can be explained by the fact that Martinez *et al.* (2010) used fillet muscle samples rather than homogenised by-product fractions.

Strategic utilisation pathways

It should be a top priority to strategically manage by-products to maximise the edible yield from whole fish for direct human consumption, according to the *Food Recovery Hierarchy for Fish By-products* (Stevens *et al.*, 2018). Heads, frames, and trimmings from all species assessed in this study show potential to increase the food supply. For example, 10% of the Norwegian salmon by-products (heads and frames) are considered a high value export product to Asian countries where they are used in e.g. soups (Stevens *et al.*, 2018). Another pathway could be the utilisation in processed foods, such as fish sausages, sauces, cakes (FAO, 2018). Based on the crude protein, EPA and DHA results, skin, trimmings and frames from Atlantic salmon, European seabass, gilthead seabream and turbot show potential for these types of applications, assuming separation is economically feasible. Alternatively, a higher economic value might be obtained if these by-products were processed in food extracts and nutraceuticals. This could be the case for salmon by-products processed into protein powders, hydrolysates, salmon oil and collagen supplements (Stevens *et al.*, 2018). On a crude protein, lipid, and EPA+DHA level, the analysis indicates potential for the heads, frames, trimmings, and skin for most species (except common carp, and turbot heads) for these types of applications. A full cost-benefit and market analysis has not been performed but is a pertinent area of future research.

If by-product quality is too low and the requirements to maintain “food quality” with appropriate HACCP and GMP standards too costly or prohibitive in any way, feed ingredients, such as FM and FO may be more appropriate (Glencross, 2019; Stevens *et al.*, 2018). This is particularly the case for viscera which has little to no value for direct human consumption but showed excellent nutritional properties for oil extraction and hydrolysis, as is the case for Atlantic salmon in Norway (Aspevik, 2016; Deepika *et al.*, 2014), showing a similar fatty acid profile compared to a salmon fillet (Sun, Xu and Prinyawiwatkul, 2006). The study indicates potential for feed applications for by-products, such as skin and viscera from all species (except common carp) due to high protein and EPA+DHA content, but low ash content. Atlantic salmon heads, frames and trimmings also show potential, as their ash content is relatively low compared to the other species. In a controlled environment they could be processed into fish protein hydrolysate (FPH), showing high-ranking nutritional characteristics, such as an excellent amino acid composition and digestible proteins that are often applied in animal feed due to their odour and flavour (Kristinsson and Rasco, 2000; Chalamaiah *et al.*, 2012; Tilami and Sampels, 2017). The analysis indicates that high volume by-products for

Atlantic salmon, could be used to produce FPH, but also peptone and oil in countries with high (secondary) by-products availability of heads, frames, and trimmings. Poland shows the largest potential volume for such value-added marine ingredients, as a result of the large secondary processing activities, resulting in e.g., frames and trimmings, while primary processing activities in Norway and UK resulting in viscera could be processed into high volumes of FO and dry peptones. The FO that could be produced from peptone manufacturing, is around 10% of the around 160 thousand tonnes of high-quality FO used by the Norwegian salmon industry within its feed supply in 2016 (Aas, Ytrestøyl and Åsgård, 2019a). Alternatively, when small volumes of fish by-products are available, a simple and inexpensive method could be the preservation by acid silage. This has a relatively lower quality compared to FPH, but is considered an inexpensive ingredient or feed additive (Olsen and Toppe, 2017). These by-products and derived ingredients could contribute to the human food chain indirectly through livestock or pet food ingredients, adding to the global pool of marine ingredients, especially where by-products exhibit high levels of valuable omega-3 fatty acids (Newton, Telfer and Little, 2014; Rustad, Storrø and Slizyte, 2011). This could be more efficient than their use for direct human consumption, especially when the flesh is technically difficult to extract and/or whole by-product is utilised, rather than just the obtainable flesh yield (Newton, 2020). It could also reduce the need for commonly used marine ingredient substitutes, such as plant ingredients, which affect EPA+DHA content in the final aquaculture product (Sprague, Dick and Tocher, 2016) and increase the pressure on agricultural resources (Malcorps *et al.*, 2019a). The inclusion of relatively “low economic value” fish by-products in aquafeed reduces the demand for pelagic fish in the form of marine ingredients. This results in a lower Fish In : Fish Out (FIFO) ratio, creating economic and environmental incentives to utilize by-products (Kok *et al.*, 2020).

Alternatively, industrial application could be considered as they might be more lucrative such as cosmetics (Alves *et al.*, 2017), pharmaceuticals (e.g., bandages) (Rothwell *et al.*, 2005; Afifah *et al.*, 2019; Sharp *et al.*, 2012) and packaging (de la Caba *et al.*, 2019). Fish skin offers opportunities for the extraction of collagen and gelatine, as a more religiously acceptable source than bovine or porcine (Nurilmala *et al.*, 2017) and applications in the fashion industry in the form of fish skin leather (Palomino, 2020).

Challenges associated with the strategic utilisation of by-products

Processing and hence, by-product utilisation strategies depend on the broader food environment, including consumption preferences that can vary greatly across Europe from whole fish compared to various processed forms of different species (EUMOFA, 2017). Additionally, fish and seafood could contain chemical contaminants with associated health implications (Thomsen *et al.*, 2021), and requires investments in HACCP and decontamination to meet food grade requirements. This also accounts for fish by-products processed into aquafeed ingredients such as protein meals and oils, in which these contaminants could cause a significant reduction in nutritional value, food safety and even fish health (Glencross *et al.*, 2020).

Countries and industries face major infrastructure challenges, such as the scale and accessibility of processing facilities, which limits the economic incentives to utilize by-products (Tyler, 2019). Additionally, obtaining certain ingredients from by-products has technological challenges and is often a cost-intensive process, consequently favouring cheaper alternatives (Olsen, Toppe and Karunasagar, 2014). Automated systems (Torrissen *et al.*, 2011), which have been successfully implemented in the poultry industry (Asche, Cojocaru and Roth, 2018), require significant capital investment.

Apart from higher uniformity and freshness of aquaculture by-products compared to those from most fisheries (Newton, Telfer and Little, 2014), feed ingredients influence the nutritional quality of the final aquaculture product (Kwasek, Thorne-Lyman and Phillips, 2020; Sprague *et al.*, 2020). Contaminant levels in farmed salmon in Europe is generally lower compared to wild salmon, which can be explained by quality control in the ingredients used (Lundebye *et al.*, 2017; Glencross *et al.*, 2020; EFSA, 2012). The suitability of by-products as feed ingredient depends on multiple factors but their widespread use requires a standardized assessment process to evaluate quality and reduce risk (Glencross, 2020). A separate issue are the legislation and documentation requirements which can be a key utilisation barrier (Olsen, Toppe and Karunasagar, 2014) for processors to meet necessary conditions and standards.

Economic potential of increased processing

The largest demand for live or whole common carp is in December during the Christmas period and this results in a large volume (up to 80-90% in the Lower Silesia) of live common carp on the market (Raftowicz and Le Gallic, 2019). The decentralized nature of the traditional farming locations makes it more difficult to process the common carp efficiently and collect by-products. However, there is also a link between the sale of live common carp and the opportunity that exist to increase the industry's (economic) output without the increase of carp ponds or additional resources. This was confirmed by the surveyed value chain stakeholders (CH3) indicated potential for year-round processed carp products to increase the profitability of the industry. The theoretical economic potential was confirmed by the carp processing model (CH3.3.3) with price data obtained from value chain stakeholders for traditional and new product forms, indicating an optimistic increase in value output of approx. 20-25%, if common carp is fully processed and strategically utilised. The model indicates opportunities to increase value output by the sales of a different portfolio of commodities and strategic utilisation of by-products. Nevertheless, prices are variable, and value output also depends on the utilisation pathway of the by-products. Additionally, consumer preferences towards different carp products forms were considered as a source of uncertainty by the surveyed stakeholders. This can be explained by the fact that the industry is in transition from traditional live common carp sales towards processed products, driven by the negative consumer perspectives (as a result of negative messaging from NGOs and media) towards the traditional practice. This new area brings uncertainties for farmers, producers, and retailers, but also new opportunities. During the value chain survey, stakeholder actors indicate that diversification of activities at the farm (e.g., tourism) could also be an appropriate strategy to increase profitability of the industry, which has been confirmed by findings in the study of Raftowicz *et al.* (2019), and therefore making it less reliant on subsidies from the EU. These activities can be combined with a culinary event where (local) tourist can be introduced to new carp products, creating awareness and acceptance of a diversified carp product portfolio.

Future research

The low sample size could be expanded in future research and a broader sample set (incl. fillets) from different farms (and feed formulations) could be taken into account. The nutrient analysis could also have been expanded with key amino acids, selenium and vitamins (Lund, 2013; Tilami and Sampels, 2017).

Blood from slaughter facilities represents around 2% of the total production volume (Stevens *et al.*, 2018), but was not investigated in this study. It shows potential for high value applications in the pharmaceutical industry (Sharp *et al.*, 2012).

Policies to support the circular economy

European aquaculture, as part of the global food system, needs to innovate to become more sustainable and competitive. In terms of the circular economy, it is crucial that circularity opportunities in aquaculture are properly defined. This includes the standardization and a common definition and understanding of circular aquaculture, which is a broad topic and does not only include the utilisation of by-products (Balsells *et al.*, 2022). Nevertheless, in this Chapter I only focus on the utilisation of aquaculture by-products as a concept with the aim to produce renewable biological resources into value added products, such as food, feed, biobased products and possibly bioenergy. The potential depends on the type of production system and therefore it is important that stakeholders are engaging in product flows to highlight circular economy opportunities, while also increasing traceability for food safety purposes. In relation to sustainability and the utilisation of by-products, knowledge based development using specific and standardized circular sustainability indicators is important so that “progress” can be measured (Balsells *et al.*, 2022). Additionally, the aquaculture sector should be encouraged to report their circularity indicators with the industry, but also on final products for the consumer. In terms of the environment, feed production is responsible for most of the impact of fed aquaculture production (Bohnes *et al.*, 2018). While the demand for sustainable proteins sources for feed is increasing (Nagappan *et al.*, 2021), readily available by-products could fulfil an important function as a virgin resource in order to reduce the dependency on marine and terrestrial ingredients, such as FM and soy (Balsells *et al.*, 2022). Conclusively, it is important to encourage sectorial and cross-sectorial co-governance, especially in relation to circular feed solutions, as other agricultural sectors are facing similar challenges. This might include a review and possible adjustments to national and EU regulations, as well as new circular research projects and collaboration to support circular economy principles in aquaculture as efficient as possible (Balsells *et al.*, 2022).

4.5 Conclusion

Our analysis showed that most farmed Atlantic salmon is processed, resulting in large available quantities of nutritious by-product volumes in Europe for food, feed, and industrial applications. While species farmed in Southern Europe, such as European seabass, gilthead seabream and turbot, showed interesting nutritional characterisation, consumer preferences towards whole fish results in less available by-products. For species with low fillet yields, such as gilthead seabream and turbot, the level to which value can be added to the by-products could significantly affect the profitability of production, because of similar total edible yields across the European species. However, sorting and utilising may not always be cost competitive where markets for separated by-products remain undeveloped.

There is potential to increase by-product volumes in the South of Europe, as well as value addition for the Norwegian aquaculture industry. Aquaculture processing by-products are an underutilised resource, which has the potential to support the sustainable intensification of European and global aquaculture if more strategically utilised. Nevertheless, their potential is dependent on available volumes and nutritional composition, which can have a significant impact on the risk involved in using them.

Most by-products show potential for direct human consumption, but this requires processing and transformation into attractive products, and the incentive to do so, which has hitherto only occurred within the salmon industry (Torrissen *et al.*, 2011). Alternatively, by-products that are unattractive for food products might be better direct into feed or industrial applications, such as cosmetics (Alves *et al.*, 2017), pharmaceuticals (e.g., bandages) (Rothwell *et al.*, 2005; Afifah *et al.*, 2019; Sharp *et al.*, 2012; Li *et al.*, 2021) and packaging (de la Caba *et al.*, 2019). Fish skin offers opportunities for the extraction of collagen and gelatine, as a more religiously acceptable source than bovine or porcine (Nurilmala *et al.*, 2017) and applications in the fashion industry in the form of fish skin leather (Palomino, 2020). Nevertheless, the most strategic application also requires an economic analysis to determine market acceptability. This would mean an expansion of the carp processing model, also including cost of storage, labour, and packaging.

This analysis showed the potentially available volumes, nutritional characterisation, and a common carp processing case study, indicating that by-product separation could offer better opportunities to maximise value addition and nutritional efficiency. This could create processing and utilisation incentives, overcoming infrastructure and legislative barriers, which could enable the aquaculture industry to diversify its products, while using marine resources more efficiently. Consequently, increasing aquaculture output in terms of volume and value without using more resources, showing a perfect example of sustainable intensification.

CHAPTER 5: ENVIRONMENTAL PERFORMANCE OF FEED

5.1 Introduction

Feed ingredients play an important role in the intensification of aquaculture production in order to meet global demand for seafood (Hua *et al.*, 2019). Feed formulations (e.g., Table 5.1 and 5.2), are a mix of ingredients meeting the nutritional requirements of the farmed animal, while they are also the most significant source of many of the environmental impacts of fed aquaculture production (Bohnes *et al.*, 2018). In addition, feed ingredients typically contribute more than 50% of aquaculture production costs (Rana, Siriwardena and Hasan, 2009). It is therefore crucial to find the right basket of ingredients, which are available, affordable, have a low environmental footprint and most importantly, meet the nutritional requirements of the farmed fish.

Historically, certain (carnivorous) aquaculture species, some of them farmed in Europe, such as Atlantic salmon, have shown a dependency on FM and FO (Naylor *et al.*, 2021). When it comes to the marine ingredients, these fulfil an important nutritional role in aquaculture diets, providing essential macro- and micro-nutrients, while it also stimulates consumption and digestibility of the feed (Glencross, 2020; Newton *et al.*, 2022). Marine ingredients also fulfil an important role in ensuring nutritional sufficiency during the early live stages of many fish species (Glencross, 2020), while their strategic use in diets also resulted in a final product ready for human consumption being high in omega-3 fatty acids (Sprague, Dick and Tocher, 2016). FM is considered a strategic ingredient due its high nutritional value, including protein, lipids, carotenoids, vitamins (B12, choline, niacin, pantothenic acid, and riboflavin), trace minerals (calcium, phosphorous) and other biologically useful ingredients (Glencross, 2019). Nevertheless, a growing demand for seafood, and finite supply of marine ingredients has resulted in feed manufacturers decreasing the inclusion level of FM and FO (Naylor *et al.*, 2009; Pelletier *et al.*, 2018; Froehlich *et al.*, 2018). Sustainability concerns in the context of “ocean health” (Tlusty *et al.*, 2019) and economic incentives have resulted in a shift towards crop-based ingredients (Pelletier *et al.*, 2018; Froehlich *et al.*, 2018; Gatlin *et al.*, 2007), such as high levels of soy fed to salmon (Newton and Little, 2018). More specifically, meals and concentrates derived from soybean for European livestock feeds are mainly imported from South America with associated concerns around deforestation (FAO, 2006; Robinson *et al.*, 2011; Torrissen *et al.*, 2011; Tritsch and Arvor, 2016; Costa *et al.*, 2017). Additionally, crops like soybean contain Anti-Nutritional Factors (ANFs), which limit the use in feed for certain species, especially carnivorous fish, such as salmon and juveniles. In order to avoid intestinal and immune implications, soybean is often processed into soybean protein concentrate, which has a significantly higher (e.g., protein) nutritional value than soybean meal (Peisker, 2001).

The substitution of marine ingredients with plant products, such as soy derived ingredients, has resulted in a shift in pressure from the marine environment towards sensitive terrestrial eco-systems (Newton and Little, 2018; Malcorps *et al.*, 2019a). Additionally, substitution could compromise health and welfare of the cultured animal (Rana, Siriwardena and Hasan, 2009; Saito *et al.*, 2020), and micro- and macro nutrient levels in the final consumed product (Sprague, Dick and Tocher, 2016; Nichols *et al.*, 2014; Saito *et al.*, 2020). More specifically, FO is rich in n-3 LC-PUFA, but its replacement in salmon diets with vegetable oils (richer in n-6 PUFA) over the past decades has resulted in a change in their fatty acid composition, highlighting the important role of marine ingredients in the aquaculture diet to maintain the quality of the final product for human consumption (Sprague, Dick and Tocher, 2016).

Aquaculture processing by-products show interesting nutritional characterisation to be included in aquafeeds, but their use is limited by legislation, scalability, and infrastructure barriers (Malcorps *et al.*, 2021c; Albrektsen *et al.*, 2022; Stevens *et al.*, 2018). Additionally, there is an increasing number of (novel) ingredients on the market that claim to support sustainable salmon production, as mentioned in the review by Albrektsen *et al.* (2022). This includes micro- and macroalgae, zooplankton, crustaceans, bacteria, yeast, insect species, as well as animal by-products, such as poultry meal and bone meal (Albrektsen *et al.*, 2022). In addition, to the evaluation of the nutritional and environmental potential of these ingredients, processing and refining methods (e.g., reducing ANFs and other contaminants) should be assessed (Albrektsen *et al.*, 2022). While some novel ingredients show nutritional potential to be included in fish diets, they could be limited by a variable nutritional quality, availability, and price issues (Pelletier *et al.*, 2018; Hua *et al.*, 2019). High energy demands and/or low production efficiency of some other ingredients, such as microalgae produced in photobioreactors, and insects, do not always deliver on the promises to improve the environmental sustainability of aquafeeds (Maiolo *et al.*, 2020b). It is important to assess and validate these environmental sustainability claims using tools such as a Life Cycle Assessment (LCA) to make sure that substitutes do not cause an increase in pressure on the marine and terrestrial environment. I therefore focus on ingredients with nutritional potential produced in dry (arid) areas. Rainfed agriculture production for these crops would not compete with other conventional crops for fertile land or other important resources, such as freshwater. I therefore selected microalgae (meal) produced in an arid region in open saline ponds, and guar meal from agricultural production in the (semi-) arid areas of India. Both ingredients are increasingly being incorporated into aquafeeds.

Microalgae can be produced in several different ways with various trade-offs. In this research, primary data from an open pond system in an arid region was modelled. Due to being open systems, control of the amount and species ratio of the mixed diatoms that dominate production is limited and therefore the nutritional content of the harvest will vary. The ponds are filled with seawater and nutrients added. The ponds do not require freshwater input, which is scarce in the area (Confidential, 2021).

Guar or cluster bean (*Cyamopsis tetragonoloba*) is grown in arid and semi-arid areas, mainly in India and Pakistan, mostly without irrigation (Ecoport, 2010; Ecocrop, 2010; Undersander *et al.*, 1991; Wong and Parmar, 1997; Tran, 2015). Guar is a legume that conserves soil nutrient content, as it is capable of fixing nitrogen, while it also shows potential for mixed cropping practices as it produces nitrogen-rich biomass (Whistler and Hymowitz, 1979; Mudgil, Barak and Khatkar, 2014; Undersander *et al.*, 1991). Consequently, guar is a crop that is mostly extensively grown without the need for irrigation (blue) water and a limited amount of fertilizer application is sufficient. Production of guar is mainly driven by its seeds production. Guar seeds show interesting nutritional values for protein (22.9-30.6%), fat (2.9-3.4%), carbohydrate (50.2-59.9%) and ash (3.0-3.5%) content (Kays, Morris and Kim, 2006). Additionally, according to Khalil (2001) crude protein levels of the seeds can be up to 32%. The seeds can be processed into guar splits (yield of 27-35%, ground to produce guar gum) and guar meal (yield 65-73%) with a protein content of approx. 42% (Kumar and Singh, 2002; Prajapati *et al.*, 2013). The demand for guar gum has increased and most of the production is used by the oil and shale gas industry (Mudgil, Barak and Khatkar, 2014; Kuravadi *et al.*, 2013; Dezember, 2011; Sood and Paliwal, 2012). Consequently, guar meal is considered a by-product (mixture of germs and hulls, with a 40% dry matter protein content), which often requires processing to improve palatability and remove ANFs to be suitable as a feed ingredient (Tran, 2015).

LCA shows promising characteristics to assess the environmental performance of microalgae meal and guar meal in aquaculture diets. LCA is an important tool for assessing the global environmental impact of a given products at a broad level. It provides insight into the environmental impact and its contribution from cradle to grave. It is an ISO (2022) standardised tool that can be used to assess (environmental) impacts from raw materials abstraction, processing, manufacturing and consumption. In some cases, it can also include the disposal of the final products, depending on the goal and scope. An LCA includes a combination of different life cycle inventories (LCIs), which form the different components of a process or a system. To assess the impacts, the emissions associated with the individual LCIs are combined. However, the emissions originating from the manufacture, use and disposal of products are often complex in terms of their diversity and quantities. This makes it hard to compare these emissions between products and systems studied. Therefore, the LCA software (SimaPro) converts the cumulative emissions from the LCIs into equivalent emission impact categories (e.g., GWP kg CO^2 equivalents).

The environmental impact can be assessed through the selection of different impact categories ranging from mid-point (single environmental impact categories) or endpoint (e.g., effect on human health, biodiversity or resource scarcity) (Bare *et al.*, 2000). The mid-point approach from the CML-IA (baseline) (2016) was preferred in this analysis, as I would like to compare the different feed formulations, change in ingredients, and associated trade-offs between the environmental impact categories. However, some impact categories are more relevant than others, while the ones available in CML-IA were not all sufficient to gain a clear understanding of the environmental trade-offs in changing feed formulations. Therefore, I have created a list of impact indicators relevant to feed use. The impact phase is followed up by the analysis and interpretation of the data followed up by the critical review phase where the methodological choices, assumptions, and limitations of the LCA are discussed (ISO, 2022).

LCA avoids problem shifting between different stages of the cycle and between impacts, which has sometimes been a criticism of other environmental impact assessment tools (Ayer and Tyedmers, 2009). For example, a study by Newton *et al.* (2018) found that most of the impact of Atlantic salmon production in Scotland occurred abroad at feed sourcing locations. Therefore, a global scope is crucial for this analysis, as most feed ingredients are produced in other continents. Additionally, Albrektsen *et al.* (2022) and Winther *et al.* (2017) highlighted the importance of including a land-use change (LUC) assessment in the carbon footprint (GWP), because feed ingredients should be produced without the need to convert natural ecosystems to agricultural land.

Despite the ISO standards, there is still a certain amount of subjectivity and options. This includes, but is not limited to, sets of representative systems or countries in a suitable format, and methodological choices, such as allocation strategies, which could cause large differences in environmental impact (Avadí *et al.*, 2018). Consequently, leading to conflicting conclusions. Therefore, comparing LCA studies with different approaches can be problematic (Avadí *et al.*, 2018). This is especially the case when studies are not fully transparent about the methodological choices which have been made. As Henriksson (2015) highlighted, conclusions could be supported if quantitative uncertainty approaches in LCI data and methodological LCA choices were adopted and clearly explained. Therefore, in relation to this analysis, methodological choices will be explained in detail in the following sections, starting with the system boundaries and functional unit, followed up by allocation, cut off criteria and LCI data collection, and methodology choices of the impact assessment. It is aligned as best as possible with the recommendations as stated in the Product Environmental Footprint Category Rules (PEFCR) for aquaculture (EC, 2016) and in particular with the PEFCR Feed for food producing animals (2018b).

5.2 Methodology – goal and scope

This section includes the methodology approaches to assess the environmental performance of microalgae meal and guar meal in different feed formulations. This includes an explanation of the LCA approach according to ISO (2018; 2022) goal and scope, system boundaries, functional unit, allocation, cut-off criteria, impact assessment methods and interpretation. In the section on cut-off criteria and LCI data collection more details are provided on the assessed system and the requirements of the specific processes included. This section also includes details on data collection for microalgae and guar.

5.2.1 System boundaries and functional unit

The system boundaries are associated with the function of the system. The function of feed formulation is to grow farmed fish. However, feed production is the most significant source of environmental impact of fed aquaculture production (Bohnes *et al.*, 2018). More specifically, according to Newton and Little (2018) more than 90% of the impact to farm-gate of Atlantic salmon farming in Scotland was embodied in feed, in which 50% of the feed came from South America, 25% from the UK, and 25% elsewhere. It is therefore crucial to conduct this analysis on a global scale considering these impacts before farm gate. The aim of this analysis is to assess the environmental trade-offs associated with the substitution of conventional ingredients, such as FM, FO, and soybean meal with microalgae (meal) and guar (meal) used in fed aquaculture production. Therefore, based on insights from CH1-2, the most relevant value chain nodes associated with the agricultural production/catch of raw materials are considered. This includes processing into feed ingredients and feed formulations, transport and feed application and performance (LCA) at the farm (Figure 5.1). It is important to consider that this analysis does not include toxic effects and the direct impacts on ecosystems and biodiversity (more info in section 5.2.5).

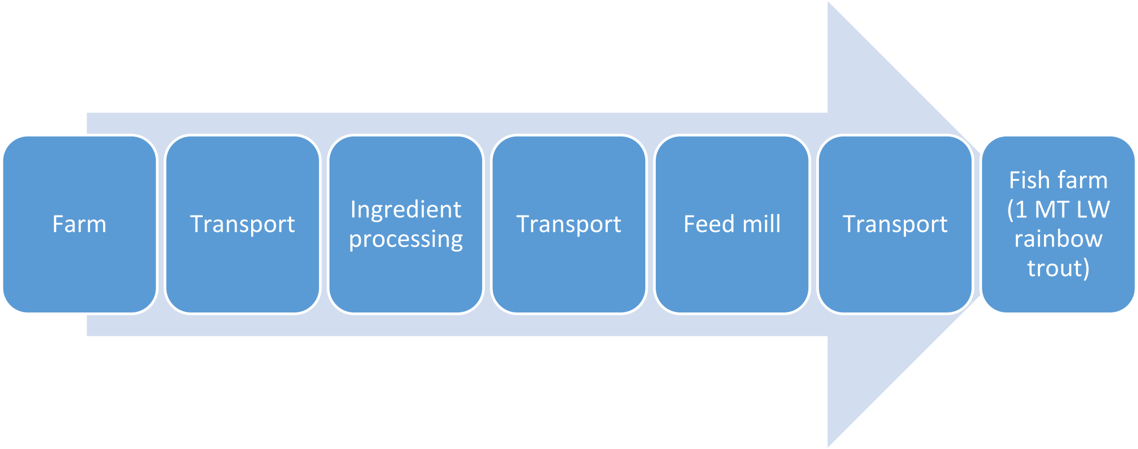


Figure 5.1: System boundaries and functional unit for the production and utilisation of feed by 1 MT LW rainbow trout at the farm.

The next step is to define the functional unit (FU), the reference unit against which impacts are compared. It is important that products can fulfil the same function rather than the absolute quantity of a product, so they can be equally compared taking nutritional performance into account, according to the PEFCR (EC, 2016). The nutritional value of feed ingredients varies significantly and therefore feed ingredients do not perform the same function in feed. Therefore, the functional unit should be based on equivalent performance to be comparable. More specifically, regarding the application and function of feed in aquaculture production, the FU should take both the production as well as the utilisation into account, which is represented by the fish farm production of 1 MT LW rainbow trout (Figure 5.1). In this regard, feed formulations including microalgae meal and guar meal and their nutritional performance (FCR) were selected from the literature.

4.2.2 Feed formulation case study

For this case study I compiled the LCI for several diets, covering a range of ingredients and feed performance (FCR) data from two different feed trial studies to explore the environmental performance of microalgae meal and guar meal as substitutes. This is based on the feed trial study by Sarker *et al.* (2020), which used four diets to completely substitute FM and FO with three microalgae species (in which I theoretically replaced the three algae species with the microalgae from the open ponds (Table 5.1)). The feed trial study of Pach & Nagel (2018) was based on four diets, which gradually substituted non-genetically modified soybean meal (non-GMO SBM) with guar meal (Table 5.2).

The feed trials differed slightly in their length (56 and 84 days), initial stocking weight (approx. 57 g and 30-50 g) and other methodological choices (stocking density, type of technology in RAS used, water parameters etc.) in the guar meal (Pach and Nagel, 2018), and microalgae meal (Sarker *et al.*, 2020) studies, respectively.

Table 5.1: Four experimental diets for juvenile rainbow trout substituting FM and FO with microalgae meal from the feed trial study of Sarker et al. (2020). For the purpose of this LCA, microalgae are produced in open ponds in an arid region.

Ingredient (%)	**Reference**	**NI[1]**	**NS[1]**	**NIS[1]**
Fishmeal (FM)[2]	7.5	0	0	0
Fish oil (FO)[2]	13.5	0	0	0
Microalgae (open ponds)	**0**	**9.4**	**9.5**	**12.6**
Canola (rapeseed) oil	0	13	12	11
Poultry by-product meal	20	20	20	20
Blood meal	7	7	7	7
Corn gluten meal	20	20	20	20
Soy protein concentrate	20	20	20	20
Wheat gluten meal[3]	5	5	5	5
$CaHPO_4$	1	1	1	1
Vitamin-mineral premix[4]	1.35	1.35	1.35	1.35
Lysine	1	1	1	1
Methionine	0.2	0.2	0.2	0.2
Wheat flour	3.5	2.1	3.0	0.9
FCR	**0.92**	**1**	**0.98**	**1**

[1] *NI referred originally to Nannochloropsis sp. + Isochrysis sp.; NS, Nannochloropsis sp. + Schizochytrium sp.; NIS, Nannochloropsis sp. + Isochrysis sp. + Schizochytrium sp., but is now theoretically substituted by a microalgae mix (confidential, open ponds) for the purpose of this LCA.*

[2] *For this analysis the FM or FO originates from 2/3 anchoveta standard (fair average quality (FAQ)) and 1/3 from Atlantic herring and mackerel by-products.*

[3] *Assumed wheat gluten meal.*

[4] *For this LCA analysis, choline chloride, ascorbic acid and astaxanthin were merged into vitamin-mineral premix.*

Table 5.2: Four experimental diets for juvenile rainbow trout substituting non-genetically modified soybean meal (non-GM SBM) with guar meal from the feed trial study of Pach & Nagel (2018).

Ingredient (%)	**Control**	**Test feed 1**	**Test feed 2**	**Test feed 3**
Non-GMO SBM	15	10	5	0
Guar meal	**0**	**5**	**10**	**15**
Fishmeal (FM)[2]	16	16	16	16
Krill meal	2	2	2	2
Poultry meal	8	8	8	8
Hydrolysed protein[3]	8	8	8	8
Blood meal	10	10	10	10
Rapeseed oil	15	15	14.9	14.8
Fish oil (FO)[2]	8	8	8	8
Wheat grain[4]	14.8	14	14.6	15.2
Wheat gluten meal[5]	1.2	2	1.5	1
Vitamin-mineral premix	2	2	2	2
FCR	**0.79**	**0.8**	**0.78**	**0.81**

[1] *Assume resource use for SBM similar to non-GMO SMB.*

[2] *For this analysis, the FM or FO originates from 2/3 anchoveta standard (FAQ) and 1/3 from Atlantic herring and mackerel by-products.*

[3] *For this analysis, I used white fish (cod, haddock, saithe) by-products for fish protein concentrate (FPC).*

[4] *Assume wheat grain.*

[5] *Assume wheat gluten meal.*

The environmental performance of the total diet was compared on a feed utilisation resolution, taking the FCR into account. The amount of feed needed to produce 1 MT LW rainbow trout at the farm was considered the most appropriate unit of comparison due to literature data available to compare the inclusion of the ingredients of interest (Figure 5.1). Applying a FU related to a single species eliminated the uncertainties associated with different edible yields, varying nutritional value or even different utilisation strategies between species, which could impact resource efficiency and therefore the environmental impact.

5.2.2 Allocation for multifunctional processes

Sometimes manufacturing processes result in several “co-products”. In that case it is necessary to allocate and attribute the environmental impact to the different co-products, and several options have been debated over the years (Svanes, Vold and Hanssen, 2011; Regueiro *et al.*, 2021). However, these options all have advantages and disadvantages depending on the situation they are applied in (Svanes, Vold and Hanssen, 2011; Regueiro *et al.*, 2021). The main principles and framework for life cycle assessment as part of environmental management under ISO 14040:2006 (2006) defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems”. System expansion, as part of the sensitivity analysis is recommended by ISO 14040:2006 (2006) and ISO 14067:2018 (2018), but this approach requires assumption in terms of the use of the co-products in other processes and consequently the avoidance of impact in these other processes (avoided burdens). However, that would assume that these co-products have the same quality and function as the materials it is substituting in the other process (Williams and Eikenaar, 2022). Another listed option by 14040:2006 (2006) and ISO 14067:2018 (2018) is the end-of-life allocation, where recycling is also seen as a multi-functional process with co-products as outputs (Williams and Eikenaar, 2022). However, this approach is not ideal, because recycling and allocation pathways are not always known. The simplest and most applied method according to ISO 14040:2006 (2006) and ISO 14067:2018 (2018) is part of the attributional approach and includes an allocation factor based on the relative mass or economic value of the co-products (Svanes, Vold and Hanssen, 2011; Regueiro *et al.*, 2021). For this analysis, economic allocation was used and the motivation was clearly stated in line with the guidelines in the PEFCR (2016; 2018b). More specifically, there is a clear relation between economic incentives and production activities to produce feed ingredients, such as fishing effort and agricultural activities. In the case of fishing, activity is generally driven by the relative price of the targeted species, compared to by-catch (Ziegler and Valentinsson, 2008). Additionally, economic allocation can be applied to the main co-products from fish processing (Ziegler *et al.*, 2003) and processing of feed ingredients, e.g., soy to soybean meal and oil (Dalgaard *et al.*, 2008). Economic allocation creates incentives for producers to reduce environmental impacts, as most of the environmental impact is allocated to the most valued products (Pelletier and Tyedmers, 2011; Audsley *et al.*, 1997; Curran, 2007). Conclusively, economic allocation is frequently used in LCA studies (related to) on fisheries and aquaculture, according to Henriksson *et al.* (2012). In line with this, economic allocation is the preferred default method in the PEFCR feed for food-producing animals' (EC, 2018b).

Circular economy principles are increasingly incentivised, and more efficient utilisation of fish by-products could benefit the nutritional, economic and environmental performance of aquaculture production (Malcorps *et al.*, 2021c; Stevens *et al.*, 2018). This is similarly applicable to the use of terrestrial by-products utilised in aquafeed. However, the significance in environmental impact reduction of different utilisation strategies, such as in feed, is highly dependent on the selected allocation method (Svanes, Vold and Hanssen, 2011; Regueiro *et al.*, 2021). The fillet for human consumption drives the fish farming production due to economic incentives, but this proportion makes up approx. fifty percent of the whole fish. The other half is considered a by-product with low economic value, albeit with interesting nutritional properties (Malcorps *et al.*, 2021c). However, in the case of mass allocation, the edible yield and the by-products (e.g., used for feed resources) carry the same proportionate impact as the fillet (Svanes, Vold and Hanssen, 2011). Consequently, the use of mass allocation at the fish processing stage results in a higher environmental footprint for by-products compared to economic allocation (e.g., Figure 5.2). Svanes *et al.* (2011) reported that fishery by-products that were utilised in feed had a Global Warming Potential (GWP) eight times larger when using mass allocation over economic, consequently, creating a barrier for stakeholders to utilise these by-products due to the associated higher environmental footprint. This clearly emphasizes the importance of applying economic allocation, as by-products have a lower economic value, which results in a relatively lower footprint, therefore creating incentives to utilize them (Regueiro *et al.*, 2021). While the application of economic allocation shows a lot of advantages, especially regarding feed use, it also has some shortcomings. Most importantly, economic volatility, over time and geographical location can result in real changes in environmental impacts being masked by these fluctuations (Svanes, Vold and Hanssen, 2011). To mitigate these effects, long term average prices are recommended by Guinée *et al.* (2004), however, this is not always possible when compiling literature data.

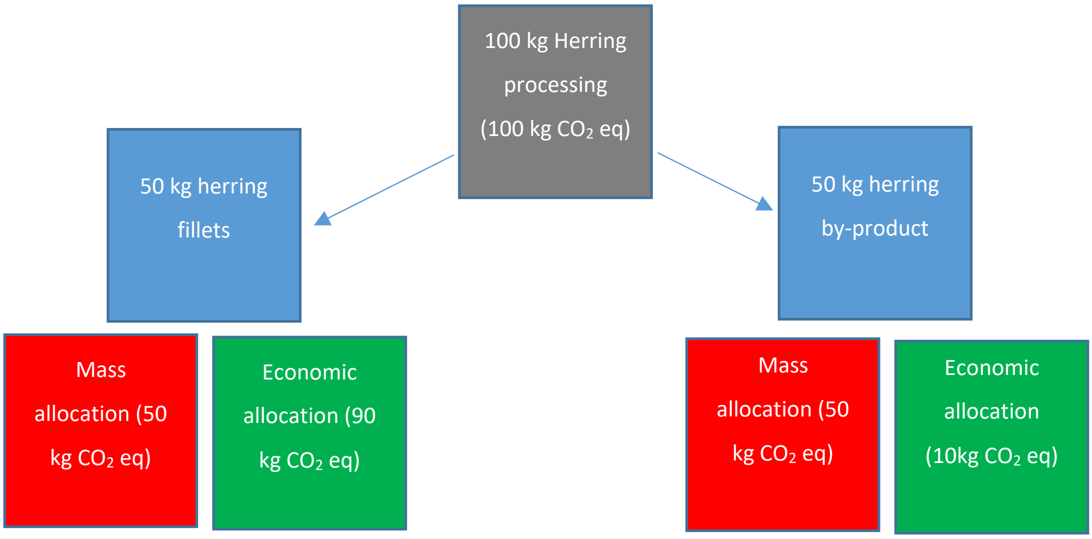


Figure 5.2: A hypothetical example adopted from the GAIN EISI report (Figure 6.1, page 33) by Newton et al. (2021b) showing two different allocation procedures and their influence on the impact results.

5.2.3 Cut-off criteria

Data evaluation is crucial to apply the correct data to the flows of materials, energy, and value within the different value chain nodes, as defined before by the system boundaries. An important process in the data evaluation is the assessment of cut-off criteria, in this case, those that have a significant amount of impact related to feed required to produce 1 MT LW rainbow trout. The most important value chain nodes were the production/catch of raw materials, processing into feed ingredients and feed formulations, transport, feed application and performance (LCA) at the farm, as shown in Table 5.3. Capital items and energy use at the fish farm is excluded from this analysis.

Table 5.3: List of ingredients (their origin and processing location if applicable) included in the feed formulations by Sarker et al. (2020) and Pach & Nagel (2018). More details available in Table A3.3.

Type of ingredient	**Ingredients**	**Raw material origin[5]**	**Ingredient storage/processing country[5]**	**LCI reference**
Marine ingredients	Fishmeal (FM)	Industry species mix, from whole fish and by-products[1]	Industry species mix (FM; Table A3.1, FO; Table A3.2)	Supplementary data in Newton *et al.* (2022), Table A3.1 and A3.2
	Fish oil (FO)			
	Fishmeal (FM)	Anchoveta standard FAQ, from whole fish, Peru	Peru	
	Fish oil (FO)			
	Hydrolysed protein	White fish (cod, haddock, saithe) by-products for fish protein concentrate (FPC)	Norway	
	Krill meal	Landed at port in Norway	Norway	
Terrestrial meal	Blood meal	Netherlands	Netherlands	Table A3.3
	Corn gluten meal	Market mix[2]	Germany	
	Guar meal	**India**	**Netherlands**	**Table 5.5 and 5.6**
	Microalgae meal (national grid energy mix[3])	**Country (confidential)**		**Table 5.4**
	Microalgae meal (renewable energy, wind)			
	Poultry (by-product) meal	Netherlands	Netherlands	Table A3.3
	(Non-GM) soybean meal	Global/market mix[2]		
	Soybean protein concentrate	Brazil, Argentina, and Netherlands	Netherlands	
	Wheat gluten meal	Market mix[2]	Netherlands	
	Wheat grain		Germany	
	Wheat flour		UK	
Terrestrial oil	Rapeseed oil		Netherlands	
Feed additives	$CaHPO_4$	France		
	Vitamin-mineral premix[4]			
	Lysine			
	Methionine			

[1] *Industry mix FM and FO based on the Skretting Environmental Footprint Report (2019) (Table A3.1 and A3.2). These mixes were applied in the feed formulations, the FM and FO from whole anchoveta were only added to compare the embodied fish category in results section.*

[2] *Global/market mix as defined by Agri-footprint (2019b): "using some "logic" and trade data on processed feed materials, Agri-footprint now also contains markets mixes of important processed feed materials like soybean meal, rapeseed meal and many others."*

[3] *The national grid energy mix of country (confidential) in Ecoinvent 3 based on the year 2014 (IEA, 2017).*

[4] *For this analysis, choline chloride, ascorbic acid and astaxanthin were also merged into vitamin-mineral premix.*

[5] *Transport includes the necessary transportation (boat/truck) from the raw material origin to the ingredient storage/processing country and transport to feed mill in Norway.*

The data collection and LCI development for microalgae meal and guar meal is described in the following section (5.2.4). The LCI's for the other feed ingredients are listed in table 5.3, and are based on well documented processes for the agricultural production, feed processing and transport (from agriculture production to processing facilities and feed mill in Norway) from "Agri-footprint – economic allocation" (2022) and "Ecoinvent 3 – allocation at point of substitution – system" (2022). The Agri-footprint database is important in this study because they cover food, feed and other agricultural intermediate products and is considered a world leading LCI in the agri-food sector (Agri-footprint, 2022). The Ecoinvent database covers a diverse range of sectors on a global and regional scale (Ecoinvent, 2022). The global scope of both databases is crucial because most aquafeed ingredients find their origin from different countries and continents. Additionally, these LCI databases were selected because they are transparent and consistent in their cut off criteria, and both use economic allocation (both LCI databases using five year average prices), which is applied to all processes resulting in co-products (Ponsioen, 2009; Paassen *et al.*, 2019a; Ecoinvent, 2022). Nevertheless, Ecoinvent and Agri-footprint do not cover the feed supplements, such as vitamin-mineral premix, $CaHPO_4$, Lysine and Methionine, which were all extracted from the AGRIBALYSE (2022) LCI database. However, vitamin-mineral premix and $CaHPO_4$ are partly based on (older versions of) Ecoinvent, in which the fabrication process was adjusted (Agribalyse, 2022). Nevertheless, inclusion rates of these supplements are low and therefore inconsistencies are negligible.

The LCI of the feed milling process was based on primary data (inputs and outputs) collected at three different feed mills in Norway in 2019. Each feed mill represented an equal share (1/3 of total weight milled) to take the variable impact among different feed mills into account (Table A3.3).

5.2.4 LCI data collection

The required data for the LCI includes manufacturing of goods and services (economic flows), as well as emitted or absorbed emissions (environmental flows), which are visualised in the flow diagram in Figure 5.3 (Guinée *et al.*, 2002). The detailed data collection for microalgae meal and guar meal is described in the following sections.

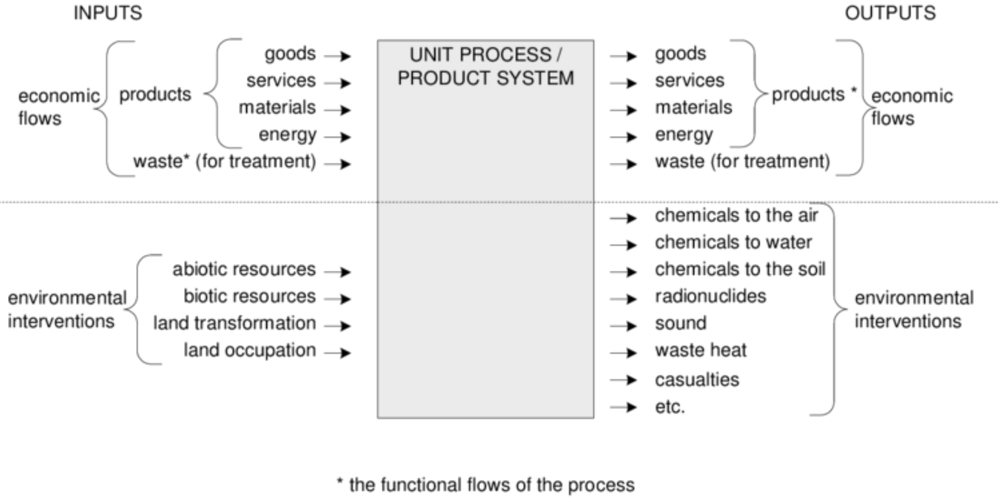


Figure 5.3: Examples of life cycle data categories by Guinée et al. (2002).

5.2.4.1 Microalgae meal

Primary data was collected through a survey, followed up by an iterative communication process by email and phone with a microalgae farm to develop an LCI ((Confidential, 2020), Table 5.4). The microalgae data was from a single producer (confidential) and is not representative for the whole industry. The data includes inputs required to produce 1 MT DM microalgae meal, such as required land, salt water and fertilizers to support biomass growth, as well as pumps and paddle wheels to transport and keep the water moving. Algae harvesting is done by primary filtration and drying the algae into a dry matter meal.

Table 5.4: Data for microalgae meal was obtained through an iterative process (Confidential, 2020) and converted to reflect the production of 1 MT of algae meal in an open pond farm in an arid region. This data is subjected to confidentiality.

[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]

**A sensitivity analysis was applied to the farm comparing the national grid energy mix (majority non-renewable, (IEA, 2017)) of country (confidential) with wind energy (electricity, high voltage {RoW}| electricity production, wind, <1MW turbine, onshore | APOS, U).*

5.2.4.2 Guar meal

The LCI for guar was compiled from literature sources, including scientific papers, reports, and websites to fill data gaps and produce industry averages, with associated uncertainties. Therefore, in this analysis several data sources were combined (where available) and then “horizontally averaged” (Henriksson *et al.*, 2013). More specifically, it is important to limit the uncertainty associated with averaged primary and secondary data from different locations and scale and diversity of production.

Therefore, using the protocol of Henriksson (2013) ensures the exclusion of outdated data, inaccurate measurements (inherent uncertainties) and user influence, while producing more accurate and representative averaged estimates by horizontal averaging and spread (variability around means). Weighted means and overall spread (SD95) were inputted (lognormal) directly in SimaPro LCA software to cover uncertainty associated with combining this sort of data within the LCIs (Table 5.5).

Table 5.5: Guar meal LCI inputs. References and their combined respective weighted mean (SD95) according to the calculated representativeness factor following the protocol for horizontal averaging of unit process data by Henriksson et al. (2013).

Reference		**Undersander *et al.* (1991)**		**Pathak, Singh and Henry (2011)[1]**		**Sharma, Dubey and Kaushik (2011)**				**Tran (2015)**		**GGC (2013)**	
Representativeness factor		**1.299**		**1.283**		**1.207**				**1.283**		**1.179**	
Input values and output (SD95)	**Weighted mean (SD95)[2]**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Seeds planted (kg/ha)	**2.35E+01 (1.34E+01)**	1.00 E+01	3.00 E+01	3.00 E+01									
Biomass/green fodder ((d)t/ha)	**4.5+01 (2.02E+00)**	4.00 E+01	5.00 E+01							4.50 E+01			
Green pods (t/ha)	**7.5E+00 (3.56E+00)**									6.00 E+00	9.00 E+00		
Crop (seed) yield (t/ha)[3]	**4.91E+00 (2.18E+01)**	5.00 E+00	8.00 E+00	5.00 E+00	6.00 E+00	5.00 E+00	6.00 E+00			7.00 E-01	3.00 E+00		
Crop duration (days)	**1.05E+02 (4.03E+00)**	6.00 E+01	9.00 E+01			8.00 E+01	9.00 E+01	1.35 E+02	1.45 E+02				
Irrigation (blue water, m3/ha)	No irrigation on large scale industrial level												
Farm-yard manure (t/ha)	**1.36E+01 (7.24E+00)**			2.50 E+01								1.00 E+01	1.20 E+01
N (kg/ha)	**1.27E+01 (n.a.)**	0.00 E+00	0.00 E+00	2.00 E+01								2.00 E+01	
P_2O_5 (kg/ha)[4]	**7.58E+01 (3.88E+00)**	9.20 E+01	1.15 E+02	6.00 E+01								6.00 E+01	
K_2O (kg/ha)	**3.88E+01 (5.14E+01)**			8.00 E+01								2.00 E+01	

[1] This literature covers two varieties of guar, namely Pusa Naubahar and Pusa Sadabahar.
[2] The calculated weighted mean and SD95 are inserted in the LCI (Table 5.6).
[3] One reference was used for average processing values of seeds into guar splits (yield of 27-35%, which are ground to produce guar gum) and guar meal (yield 65-73%) (Gresta et al., 2014). Economic allocation was applied based on a single reference for prices of guar meal (IR25/kg) (Indiamart, 2022b) and guar gum (IR95/kg) (Indiamart, 2022a) in September 2022.
[4] Some references included super Phosphate, which is converted to P_2O_5 based on: "Triple superphosphate is highly concentrated phosphorus fertilizer with contents of approx. 46% diphosphorus pentoxide (P_2O_5). It is appropriate for feeding all types of soils which have a pH within the limits of weakly acidic to alkaline medium (Agropolychim, 2022)".

Emissions from managed soils

Agricultural production is associated with different emissions, originating from crops and livestock activities, such as methane (CH_4), ammonia (NH_3), nitrous oxide (N_2O), carbon dioxide (CO_2) to air emissions with associated climate change impacts (FAO, 2020b; Smith *et al.*, 2007). Methane is released when organic matter decomposes in an oxygen-deprived environment, such as stored manure or through rice production in flooded areas (Smith *et al.*, 2007; Mosier *et al.*, 1998). Ammonia can be converted to nitrate by aerobic microbial oxidation (nutrification), while nitrate can be converted by anaerobic activities (denitrification) to nitrous oxide (Klein *et al.*, 2006). Nitrous oxide is released into the air when nitrogen in manure or the soil is transformed by microbial activities, especially when there is a surplus of nitrogen available, in combination with a wet environment (Oenema *et al.*, 2005; Smith and Conen, 2004). Wet conditions are not applicable to the production of guar seeds in arid regions. Carbon dioxide release to air is associated with the decomposition of organic matter or burning of plant litter (Smith, 2004; Janzen, 2004), and land use change (Smith *et al.*, 2007). Additionally, the use of phosphorus (P) is considered a limiting nutrient for food production (Ytrestøyl, Aas and Åsgård, 2015; Roy *et al.*, 2016; Kraan, 2010), while it use in combination with nitrogen fertilizer and emissions in water causes eutrophication and dead zones in waterbodies (Diaz and Rosenberg, 2008; Kraan, 2010; Pelletier *et al.*, 2018).

For the scope of this thesis, I used an "*Emissions from Managed Soils Model*", based on literature from the IPCC (Dong *et al.*, 2006; Klein *et al.*, 2006), with additional phosphorus and nitrogen emissions to water. This model is using verified methodologies obtained from the literature to calculate emissions to air (dinitrogen monoxide, ammonia, and nitrogen dioxide) and emissions to water (nitrate and phosphate). Methane and carbon dioxide are not separately considered for this model, because that is already included in the LCIs of the crop ingredients. Type of climate, soil, intensity of production has an impact on the different emissions. Therefore, I provided the guar crop yield production and fallow periods, irrigation, amount of nitrogen in seeds, fertilizer, and manure application from the representative horizontal average data points from Table 5.5. The most relevant emissions to air (dinitrogen monoxide, ammonia, and nitrogen dioxide) and emissions to water (nitrate and phosphate) were calculated and included in the LCI, as shown in Table 5.6.

Table 5.6: Guar agriculture production in India.

	Quantity	**SD95**[1]
INPUTS		
-Occupation, annual crop, non-irrigated, extensive, land, m^2a	2,900	Undefined
-Guar seeds, at regional storage, IN, kg	23.5	Lognormal: 1.34E1
-Manure, solid, cattle {GLO}| market for | APOS, U, kg	13600	Lognormal: 7.24E0
-Nitrogen fertiliser, as N {GLO}| market for | APOS, U, kg	12.7	Undefined
-Phosphate fertiliser, as P2O5 {GLO}| market for | APOS, U, kg	75.8	Lognormal: 3.88E0
-Potassium fertiliser, as K2O {GLO}| market for | APOS, U, kg	38.8	Lognormal: 5.14E1
-Transport, freight, lorry >32 metric ton, EURO3 {RoW}| tkm[2]	25.46	
Emissions to air[3]		
-Dinitrogen monoxide, kg	1.04E1	Undefined
-Ammonia, kg	4.63	
-Nitrogen dioxide, kg	48.79	
Emissions to water[3]		
-Nitrate, kg	114.03	Undefined
-Phosphate, kg	9.93E-1	
OUTPUTS[4]		Allocation %
-Guar seeds (*C. Tetragonoloba* and varieties) at farm (IN), kg	4,910	95
-Guar green fodder/biomass (*C. Tetragonoloba* and varieties) at farm (IN), kg	45,000	2.5
-Guar green pods (*C. Tetragonoloba* and varieties) at farm (IN), kg	7,500	2.5

[1] Undefined SD95 applicable in cases where 1 value was obtained from the literature or where (part of) multiple values were 0.

*[2] Transport of fertilizers was estimated at 200 km. Fertilizer 12.7+75.8+38.8 = 127.3 kg fertilizer / 1000kg = 0.1273 * 200 = 25.46. Annual crop occupation (m^2a) is calculated based on the total yield of 57.41 t/ha (seeds + fodder/biomass + pods) in the dry season (105 days a year).*

[3] Certain weighted means from table 5.5 were modelled in an "Emissions from Managed Soils Model", based on literature from the IPCC (Dong et al., 2006; Klein et al., 2006). The outputs of this model provided emissions to air (dinitrogen monoxide, ammonia and nitrogen dioxide) and additionally emissions to water (nitrate and phosphate).

[4] Allocation of guar seeds, fodder/biomass and green pods was estimated at 95%, 2.5% and 2.5%, respectively, based on online market prices by Indiamart (2022b; 2022a).

5.2.5 Impact assessment and characterisation

It is crucial to include a wide range of different impact categories to identify the changing pattern of impact. Impact categories for seafood production were identified by Pelletier *et al.* (2007) and have been further developed in the PEFCR "Feed for food producing animals" (2018b) (examples shown in Table 5.7). However, aquatic -, terrestrial ecotoxicity, human toxicity has been excluded from the analysis, because according to Cashion *et al.* (2016) many therapeutants and chemicals used in aquaculture are not well characterised to be included in the LCA process. Net primary productivity and biotic resources were also excluded, as these methods are not well defined for use in LCA either (Cashion *et al.*, 2016).

Table 5.7: Midpoint impact categories for seafood production.

Impact category	**Description of impacts**	**Unit/MT**	**Reference**
Cumulative Energy Use (CEU) (non-renewable)	Total non-renewable energy demand	MJ	Huijbregts *et al.* (2006) and Frischknecht *et al.* (2015)
Cumulative Energy Use (CEU) (renewable)	Total renewable energy demand	MJ	Frischknecht *et al.* (2015)
Global warming potential (GWP)	Contributes to atmospheric absorption of infrared radiation	kg CO_2 eq.	Pelletier *et al.* (2007)
Global warming (incl. LUC) (GWP LUC)	Effect of changes in land use on GWP emissions, such as deforestation.	Kg CO_2 eq.	Albrektsen *et al.* (2022) and Winther *et al.* (2017).
Ozone layer depletion (OLD)	Reduction of the UV protective ozone layer caused by emissions (CFCs, HFCs, and halons)	kg CFC-11 eq.	Pelletier *et al.* (2007)
Photochemical oxidation (PCO)	Contributes to photochemical smog	kg C_2H_4 eq.	Pelletier *et al.* (2007)
Acidification potential (AP)	Contributes to acid deposition	kg SO_2 eq.	Pelletier *et al.* (2007)
Eutrophication potential (EP)	Provision of nutrients contributes to biological oxygen demand	kg PO_4 eq.	Pelletier *et al.* (2007)
Fish in: Fish Out Ratio (FIFO)	A measure of the volume of fish inputs required	kg embodied fish	Kok *et al.* (2020)
Blue water use (BWU)	Irrigation water from terrestrial freshwater bodies	m^3	Mekonnen & Hoekstra (2011)
Land use (LU)	Area of land occupied over time.	M^2a	Pelletier *et al.* (2007)

However, the emissions originating from manufacture, use and disposal of products are often complex in terms of their diversity and quantities. This makes it hard to compare these emissions between products and systems studied. Therefore, the LCA software (SimaPro) converts the cumulative emissions from the LCIs into equivalent emission impact categories (e.g., GWP kg CO2 equivalents) using characterisation factors as shown in Table 5.8.

Table 5.8: Common characterisation factors frequently used in LCA impact categories, adapted from GAIN EISI report by Newton et al. (2021a).

Impact category	**Characterisation model**	**Reference**	**Characterisation factors**
Global warming potential (kg CO_2 eq.)	GWP 100, CML 2001 baseline	IPCC (Kirtman *et al.*, 2013)	CO_2 = 1 CH_4 = 28 N_2O = 265
Acidification potential (kg SO_2 eq.)	AP, CML 2001 non-baseline	Hauschild and Wenzel, (1998)	SO2 = 1 NH_3 = 1.88 NO_2 = 0.7
Eutrophication potential (kg PO_4^{3-} eq.)	EP, CML 2001 baseline	Heijungs *et al.* (1992)	PO_4^{3-} = 1 NH_3 = 0.35 COD = 0.022

Each environmental impact indicator in Table 5.7 used in this analysis has been described below.

Cumulative energy use (CEU)

Energy use is split up in non-renewable (fossil) according to Huijbregts *et al.* (2006) and renewable. Both quantifying the energy content of the different resources, respectively (Frischknecht *et al.*, 2015). Splitting up the energy sources enables a better understanding of the impacts and trade-offs as a result of the use of non-renewable and renewable energy.

Global Warming Potential (GWP)

GWP is the potential for GHGs, such as carbon dioxide, methane, and dinitrogen monoxide, to affect the temperature on earth. Characterisation factors for these gasses are given in Table 5.8. Regarding the trend of increasing plant ingredients in aquafeed, it is important to take the emissions into account associated with the cultivation and processing. While 23% of the anthropogenic emissions originates from agriculture, forestry and other land uses, land use changes in the form of converting a forest to agricultural land is the main driver of GHG emissions (Jia *et al.*, 2022). However, there is much uncertainty around the GHG emissions originating from land use change (LUC) (Jia *et al.*, 2022). Therefore, according to PEFCR (EC, 2018b), it is suggested to separate out GWP associated with agricultural production and feed ingredient processing and GWP LUC, as a result of recent changes in land use. This will avoid problem shifting and to make sure that ingredients are not being substituted with other ingredients that cause destruction to other ecosystems that are abroad, according to a study by Albrektsen *et al.* (2022) and Winther *et al.* (2017).

Ozone layer depletion (OLD)

The ozone layer has a crucial function to protect human wellbeing and ecosystems against an increase in ultraviolet radiation at Earth's surface. Ozone layer depletion is caused by emissions such as CFCs, HFCs, and halons (Fahey and Hegglin, 2010).

Photochemical oxidation (PCO)

PCO is also referred to as summer smog, or secondary air pollution and is measured in kg ethylene equivalents. It is a reaction of sunlight with emissions (in the troposphere), caused by the combustion of fossil fuels, defined as Volatile Organic Compounds (VOCs), such as ethane, ethylene, benzene, acetone and formaldehyde (Baumann and Tillman, 2004). It can result in damage to materials, but also to crops. Additionally it can cause human health problems (Manahan, 1994; Adeeb and Shooter, 2002).

Acidification potential (AP)

AP includes acidifying contaminants (e.g., SO_2, NO_x and NH_x) damaging the environment, such as buildings and materials, as well as agricultural crops. Acidifying materials also affect soil, waterbodies, forest and other ecosystems (Dincer and Bicer, 2018).

Eutrophication potential (EP)

EP is caused by an excessive use of nutrients (e.g., phosphorus and nitrogen), causing unwanted change in the ecosystem, such as species composition and growth in biomass in aquatic and terrestrial ecosystems (Dincer and Bicer, 2018). Excessive use of fertilizers (nitrogen and phosphorus) could cause an increase in aquatic plant growth and algae blooms leading to dead zones affecting biodiversity and ecological composition (Čuček, Klemeš and Kravanja, 2015).

Fish in : Fish Out (FIFO)

Aquaculture has often been criticised for its use of marine ingredients (mostly derived from forage fish species). Understanding the efficiency of marine ingredient inputs in aquafeeds is crucial to support the sustainable intensification of the industry, which has often employed the Fish In: Fish Out ratio (FIFO) (Naylor *et al.*, 2009). However, the various FIFO calculation methods developed over several decades have not been compatible with or not been applied to LCA methodology for various reasons, including allocation rules and boundary setting. However, the study of Kok *et al.*

(2020) presents the Fish In: Fish Out ratio based on the principle of economic allocation and is therefore applied in this analysis to calculate the embodied fish use in industry mixes of FM and FO and overall use in the feed formulations.

Blue Water Use (BWU)

There are concerns in a world with limited freshwater resources, of which agriculture consumes 70% of global resources (Salin *et al.*, 2018). Water consumption is divided into three classifications. Blue water is the volume of surface and groundwater consumed/evaporated, green water refers to rainwater consumed, while grey water is the volume required to assimilate pollutants to maintain certain water quality standards (Mekonnen and Hoekstra, 2011). Grey water was excluded from the analysis, because it is using rough estimates, while excluding important locals' details, such as soil property, slopes and rainfall and other characteristics. For example, the use of fertilizers will influence the volume of grey water required to maintain certain water quality standards. However, large assumptions were made for fertilizer application rates per crop per country (Mekonnen and Hoekstra, 2011). Green water was not analysed for consistency reasons, because rainwater was not separately included in most impact assessment methods (2022; 2019b).

Land use (LU)

LU is a crucial impact factor, especially in this analysis that includes feed formulations with large proportions of plant ingredients. A land area as large as Iceland (~10 million ha) was required to produce global aquafeed ingredients (e.g., rapeseed/canola, soybean, corn, nuts, and wheat) in 2008 (Fry *et al.*, 2016). However, it is expected that this land area is significantly larger by today, because aquaculture production volumes almost doubled in the last 15 years. Globally, agricultural land is under pressure by the increasing demand for food, feed, biofuels, biobased materials (Spiertz and Ewert, 2009; Godfray *et al.*, 2010) and the effects of climate change (FAO, 2018; Fry *et al.*, 2016). Consequently, indicating that horizontal agricultural expansion is limited and mostly at the expense of other land use (e.g., forest or protected areas) with social and environmental implications (Zabel, Putzenlechner and Mauser, 2014).

5.2.6 Interpretation and sensitivity analysis

The LCA results are compared on multiple resolutions to understand the relative impact (mitigation) of the inclusion of microalgae meal and guar meal in the feed formulations that were obtained from two different feed trial studies by Sarker *et al.* (2020) and Pach & Nagel (2018) (Table 5.1 and Table 5.2, respectively). First, I performed a contribution analysis on microalgae meal and guar meal to identify sustainability hotspots during the production process. This is followed up by a LCA of the production of 1 MT of these ingredients compared with conventional aquafeed ingredients as shown in the feed formulations. While this does not take the feed performance at the farm into account, their impact in relation to their inclusion rates in diets provides a better understanding to their relative contribution to the overall environmental impact of a feed formulation. This is followed up by the final LCA, which compared the feed formulations while taking the feed performance at the farm into account based on the FCRs provided by the feed trial studies of Sarker et al. (2020) and Pach & Nagel (2018). This resulted in an LCA comparison on a feed utilisation resolution (feed needed to produce 1 MT of fish).

A sensitivity analysis was applied to the microalgae comparing the national grid energy mix (majority non-renewable, (IEA, 2017)) of country “confidential” with wind energy at farm level.

5.3 Results

The results are presented in several stages, 1) contribution analyses of ingredient production, 2) comparisons between conventional aquafeed ingredients, 3) and a comparison of the performance of the feed formulations. A sensitivity analysis is applied throughout the results for microalgae meal production, replacing the business as usual (BAU) wind energy with the national energy grid mix in the LCI (Table 5.4). The renewable wind energy is defined as “wind”, while the non-renewable national grid energy mix of country (confidential) is defined as “nat. grid” on the x-axis throughout the results sections.

5.3.1 Contribution analysis of microalgae meal and guar meal production

The results presented in the contribution analysis include all the production steps (and relative impact) required to produce a suitable feed ingredient. In the case of microalgae, these are all the inputs required for the open ponds and the drying stage to produce microalgae meal (DM). A large advantage in this case is that the entire production of microalgae meal is vertically integrated at the farm. This is not applicable for the production process of guar meal, which is more geographically fragmented, including the agricultural production of guar seeds in India and the transport and processing in the Netherlands to produce guar meal.

The transport to the feed mill in Bergen (Norway) is not included in the contribution analysis of both ingredient production but is considered when comparing the full range of competing feed ingredients.

5.3.1.1 Microalgae meal production

Two scenarios are presented for the microalgae farm. The first one is the BAU with renewable wind energy on site. This is followed up by a theoretical scenario (sensitivity analysis) in which wind energy, defined as “wind” is substituted by the national grid energy mix of country (confidential), defined as “nat. grid”. Indicated by the patterned light colour bars in the Figures. In the case of BAU, the most significant impact across most impact categories is caused by the drying of the algae biomass, followed up by the pumping of the water in the open ponds. The relative impact across the categories for algae drying increased if the national grid energy mix (mostly non-renewable) was used on site. Additionally, despite the efforts to use renewable energy on site, the fertilizer application showed a significant contribution (approx. 30%) to the CEU (non-renewable) category. While the high energy use of drying of the algae is a significant contributor to most impact categories, the water is collected and can be used elsewhere, giving a negative BWU. However, this effect would be negligible if the national grid energy mix were used on site to meet the electricity demand. More specifically, the production of non-renewable energy in the energy mix of country (confidential, (IEA, 2017)) requires freshwater in its production stage. The land use to produce 1 MT of microalgae meal is 0.067 ha/year and can be contributed to the area occupied by the open ponds and other facilities required.

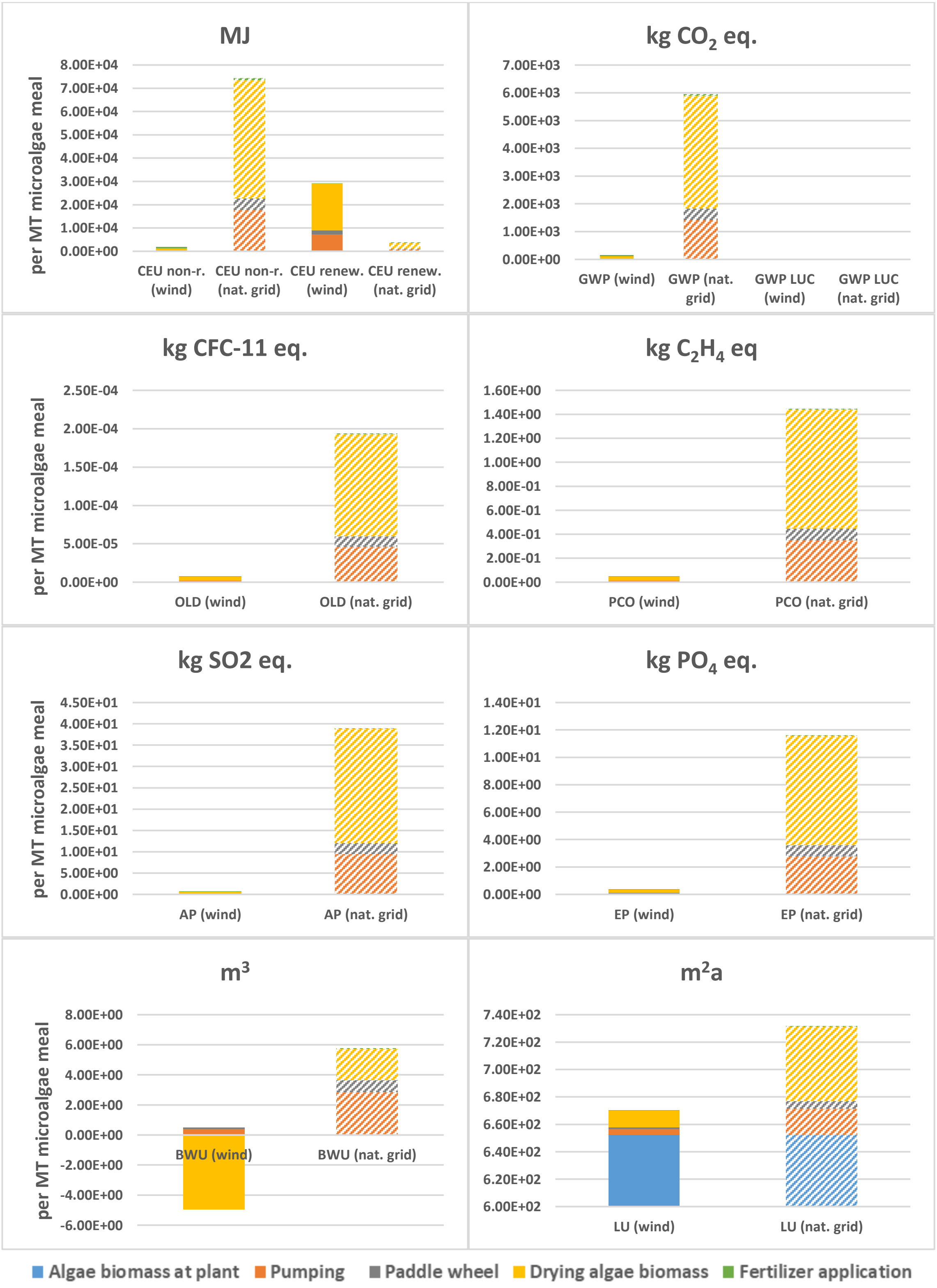


Figure 5.4: Contribution analysis of open pond microalgae production in country (confidential). The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level. Transport to feed mill in Bergen (Norway) is excluded.

5.3.1.2 Guar meal production

The production of guar seeds at the farm in India is the largest contributor to the overall impact of guar meal production (Figure 5.5). However, guar processing in the Netherlands contributes to approx. 35% of the CEU (renewable energy), and 20% of the CEU (non-renewable) energy of the total guar meal production. Interestingly, transport by a transoceanic ship from India to the Netherlands seems to be a hotspot, contributing to approx. 50% of CEU (non-renewable and renewable) and approx. 70% of ozone layer depletion.

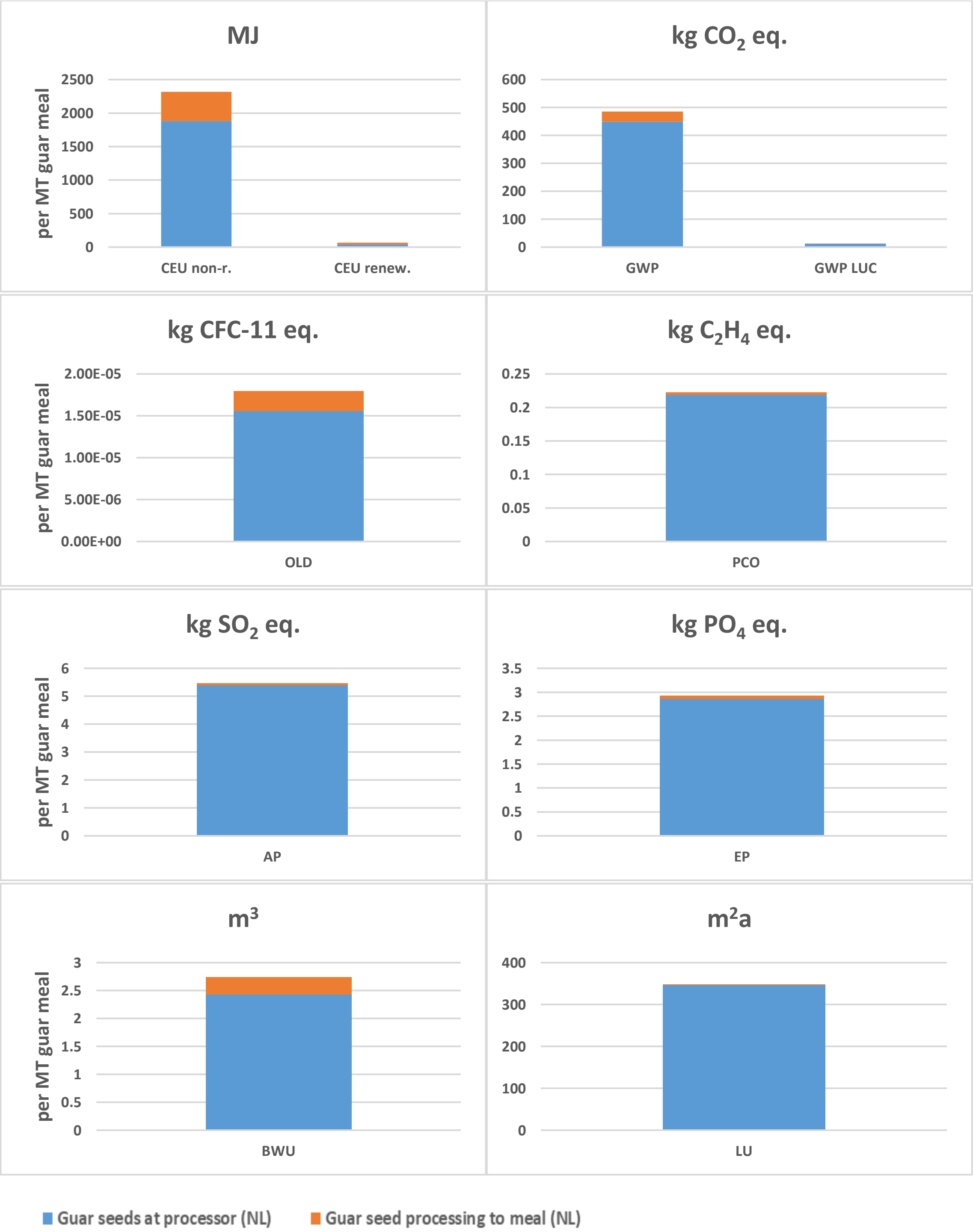


Figure 5.5: Contribution analysis of guar seeds production and processing.

5.3.2 Environmental comparison of conventional ingredients used in European aquafeeds

This analysis compared microalgae meal and guar meal with the (agricultural) production of conventional aquafeed ingredients as displayed in Table 5.3. Some ingredients require processing (and associated resources) and transport to processing facility. All transport required to produce and process the ingredients is included and detailed information on the production and processing location can be found in Table 5.3. In this analysis, the transport of the processed ingredient to the feed mill in Norway is excluded from this analysis. The patterned colour bar in Figures 5.6 to 5.9 is a sensitivity analysis comparing the national grid energy mix of country (confidential, (IEA, 2017)) with wind energy at the microalgae farm.

Overall, meals showed the largest CEU compared to oils. More specifically, microalgae meal has the largest CEU in response to the sensitivity analysis of replace wind energy with the national grid energy mix (Figure 5.6). This is followed up by wheat gluten and microalgae meal produced with wind energy. Regarding the latter, this is BAU scenario and most of the energy used in the process to produce microalgae meal comes from renewables (wind).

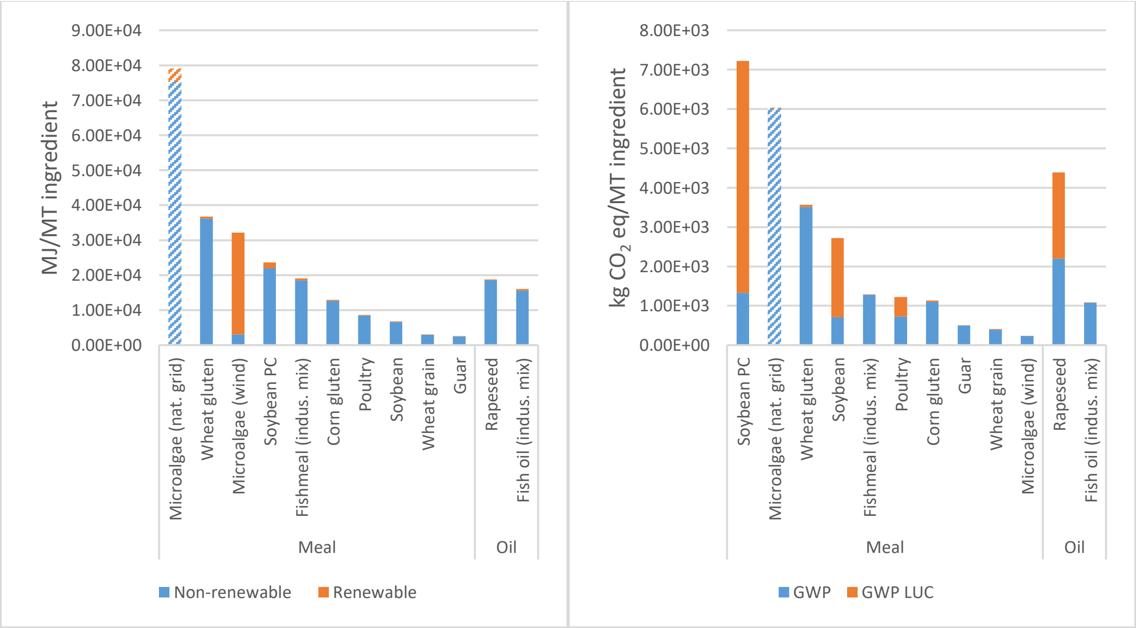


Figure 5.6: Cumulative energy use (non-renewable and renewable, left) and global warming potential (land use change, right) of conventional ingredients used in European aquafeeds. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

FM and FO industry mix (appendix A3.1 and 3.2) and microalgae meal (nat. grid) showed significantly higher impact values for OLD compared to the other meals and oils listed (Figure 5.7, left). When it comes to PCO, soybean protein concentrate showed a significantly higher impact compared to the other ingredients (Figure 5.7, right).

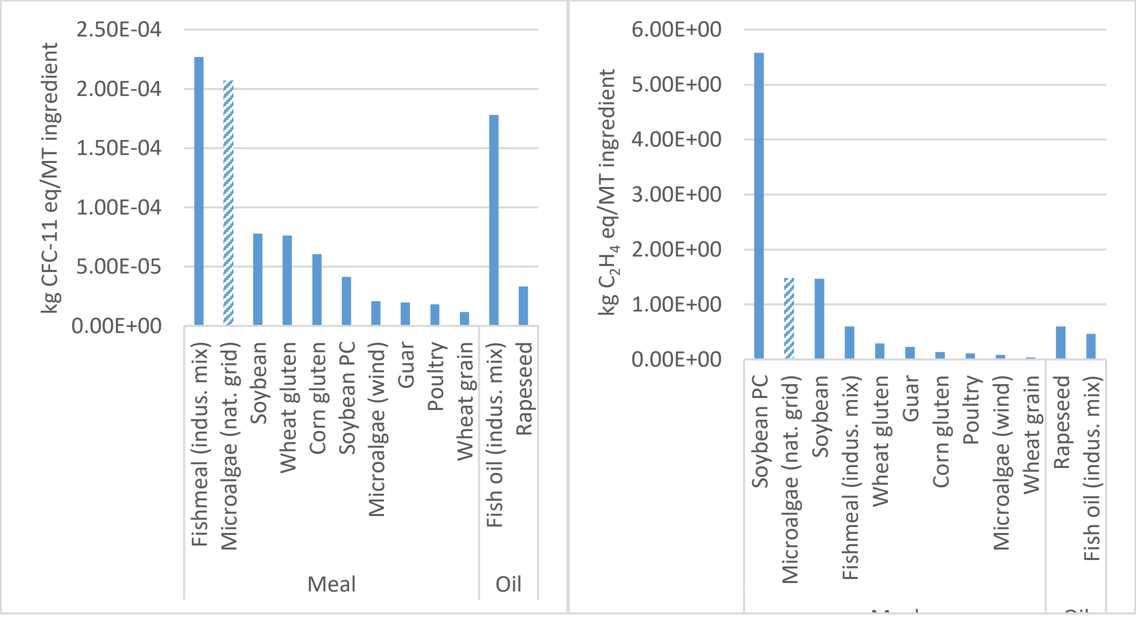


Figure 5.7: Ozone layer depletion (left) and photochemical oxidation (right) of conventional ingredients used in European aquafeeds. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

AP showed the highest impact values for microalgae meal (nat. grid), followed up by rapeseed oil, wheat gluten, FM (indust. mix) and FO (Figure 5.8, left). In terms of the EP, rapeseed oil showed the highest values, followed up by wheat gluten meal and microalgae meal (nat. grid) (Figure 5.8, right).

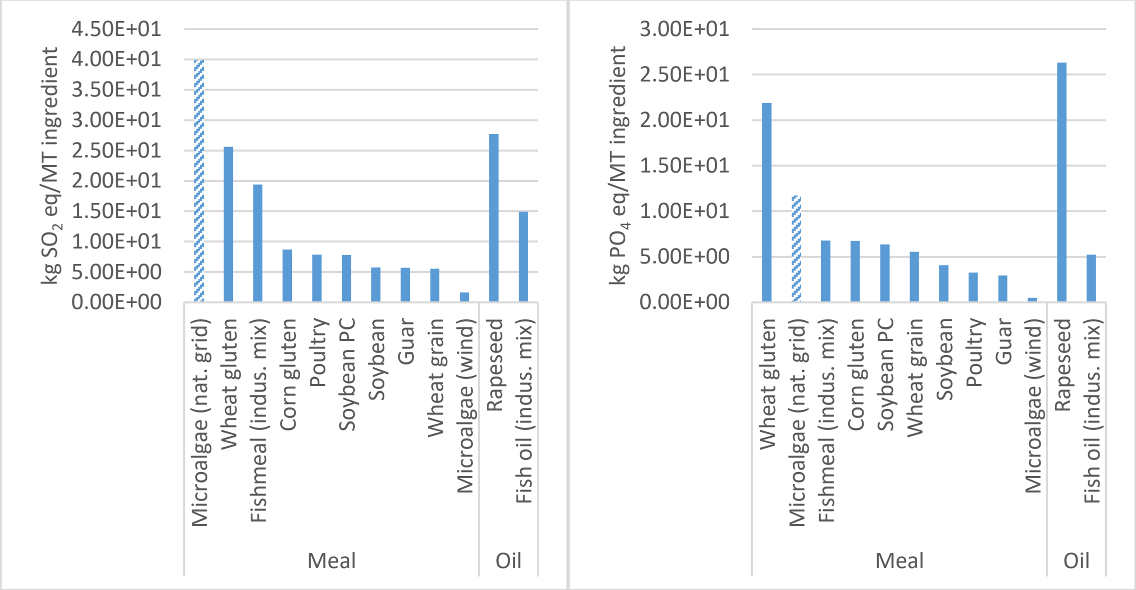


Figure 5.8: Acidification potential (left) and eutrophication potential (right) of conventional ingredients used in European aquafeeds. The light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

Corn gluten meal, FM (indus. mix) and wheat gluten meal show the highest BWU (Figure 5.9, left). Microalgae (wind) showed negative values, meaning blue water was produced rather than consumed. LU (Figure 5.9, right) is highest for rapeseed oil, followed up by soybean protein concentrate and wheat gluten meal.

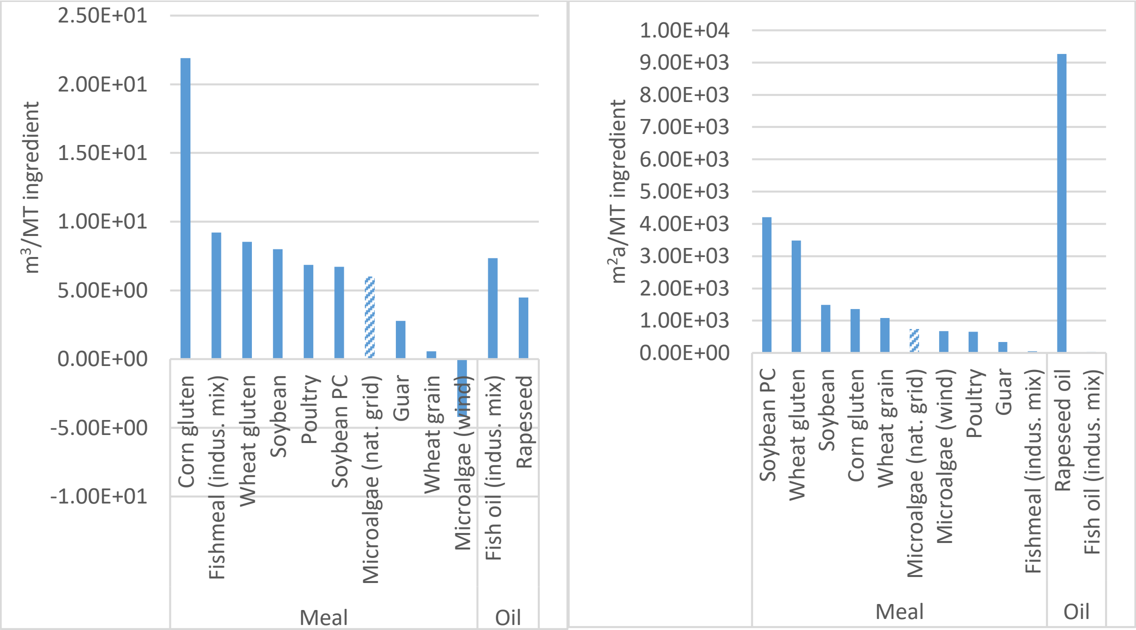


Figure 5.9: Blue water use (left) and land use (right) of conventional ingredients used in European aquafeeds. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

Embodied fish in an industry mix (FM and FO) is approx. half compared to embodied fish in FM and FO originating from whole fish anchoveta (Figure 5.10).

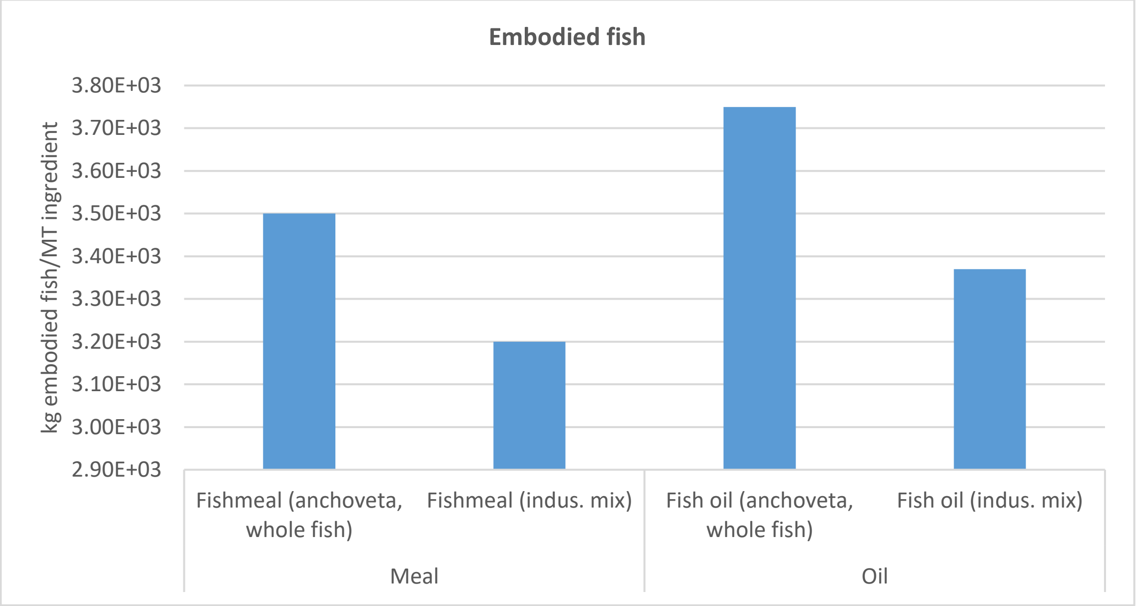


Figure 5.10: Embodied fish in the FM and FO industry mix compared with standard anchoveta FM and FO from whole fish.

5.3.3 Performance of the selected feed formulations

The ingredient inclusions of the 4 assessed diets of Sarker *et al.* (2020), substituting FM/FO with microalgae, are presented in Table 5.1. The ingredient inclusions of the 4 diets of Pach & Nagel (2018) substituting non-GMO SBM with guar meal, are presented in Table 5.2. The LCA results include the production and processing of the listed marine and terrestrial ingredients (Table 5.3), transport to the feed mill in Norway, the process of feed milling (LCI in the appendix A3.3), and transport of the finished feed (250 km by boat, 100 km by truck) to the farm. Additionally, the feed performance (FCR) at the farm, which includes the amount of feed required to produce 1 MT LW rainbow trout is included in the results. The patterned colour bar in the Figures in this section is a sensitivity analysis comparing the national grid energy mix of country (confidential) with wind energy at the microalgae farm.

The CEU (renewable and non-renewable) is highest for the feed formulations substituting FM/FO with microalgae, in particular the feed formulations that used the national grid energy mix for the algae production (Figure 5.11, left). However, when only non-renewable energy is considered, the microalgae (wind) diets showed a relatively similar CEU non-renewable profile as the feed formulations using guar meal as non-GMO SBM substitute.

In terms of GWP (excluding LUC), impact values showed similarities between the feed formulations using microalgae meal (wind) as FM/FO substitute (incl. reference) and the feed formulations using guar meal as non-GMO SBM substitute (including control) (Figure 5.11, right). However, all the feed formulations that are using microalgae meal as a FM/FO substitute showed significantly higher

GWP LUC impacts, especially the feed formulations using non-renewable energy, as a direct result of the production of e.g., hard coal, natural gas and oil in the national (confidential) grid energy mix (IEA, 2017).

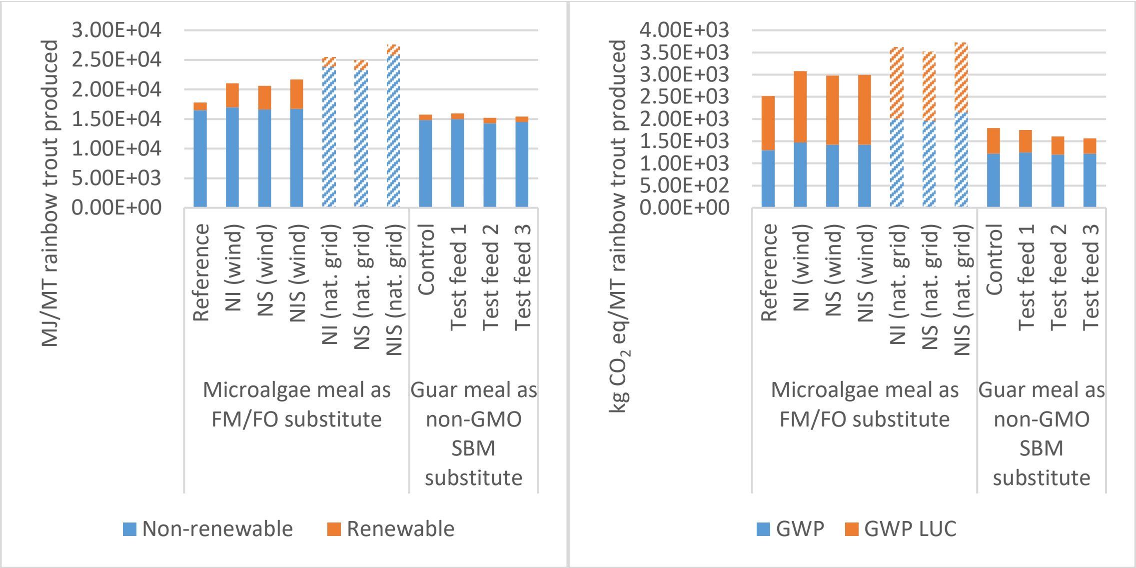


Figure 5.11: Cumulative energy use (left) and global warming potential (land use change, right) of the selected feed formulations. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

In terms of OLD, the feed formulations that used microalgae meal (wind) as FM/FO substitute (excl. reference) showed lower impact values compared with all other feed formulations (Figure 5.12, left). Nevertheless, this is reversed for PCO, as the feed formulations that used guar meal as a non-GMO SBM substitute (including control) showed significantly lower impact values for PCO compared to all other diets (Figure 5.12, right).

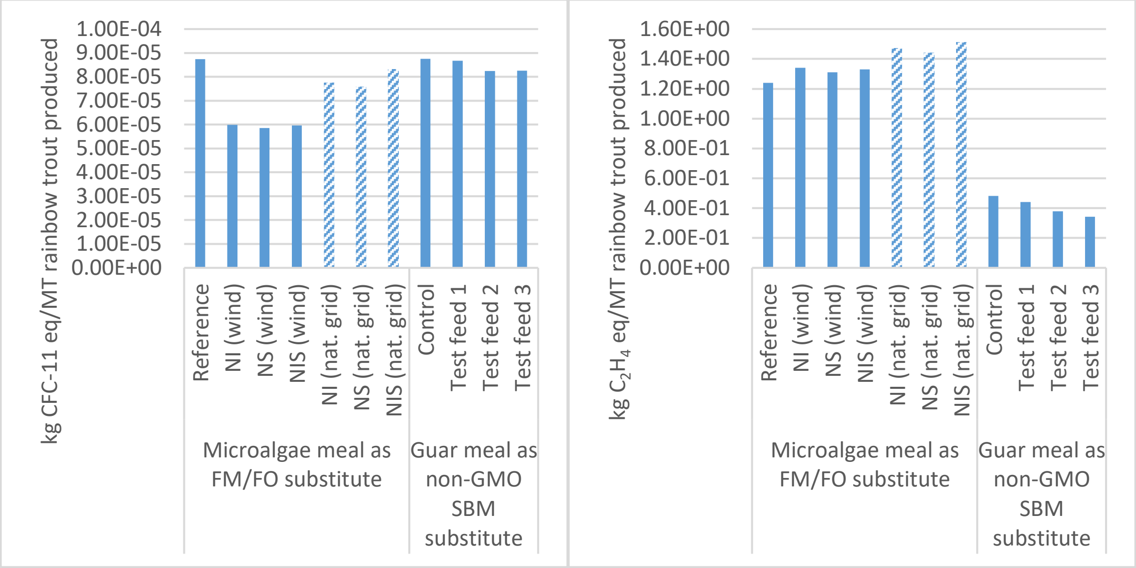


Figure 5.12: Ozone layer depletion (left) and photochemical oxidation (right) of the selected feed formulations. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

The values for all feed formulations (including reference and control) for AP are similar, except for the sensitivity analysis where the microalgae production is produced with the national grid energy mix instead of wind energy (Figure 5.13, left). In terms of the EP, impact values for the feed formulations using the guar meal as a non-GMO SBM substitute (incl. control) are significantly lower compared to the other feed formulations (Figure 5.13, right).

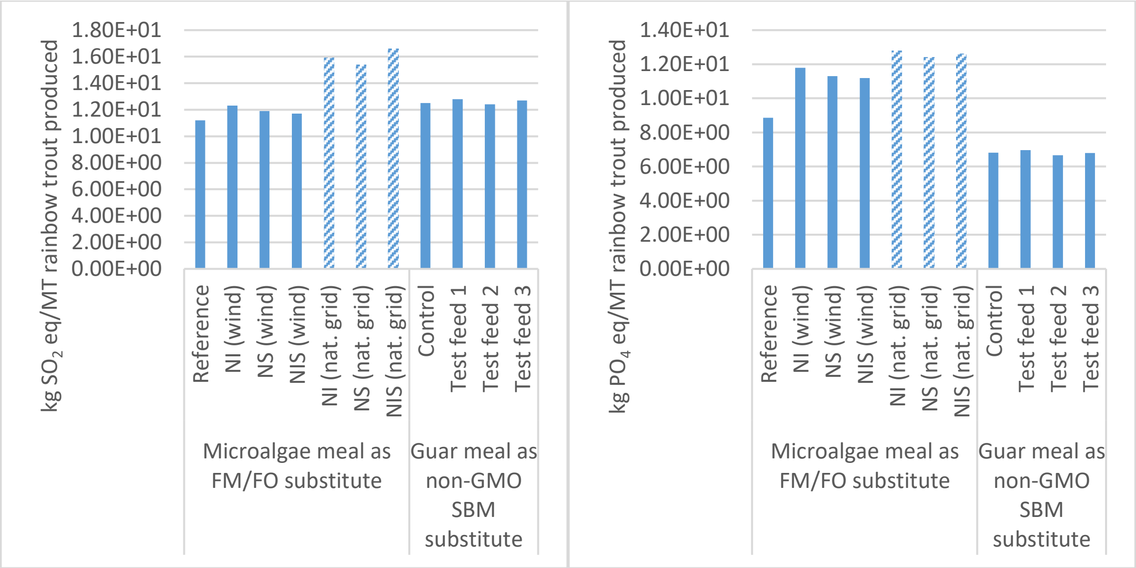


Figure 5.13: Acidification potential (left) and eutrophication potential (right) of the selected feed formulations. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

BWU was highest for the feed formulations using guar meal as non-GMO SBM substitute, while it was lowest for the feed formulations including microalgae meal as FM/FO substitute in the case where wind energy was used (Figure 5.14, right). LU was highest for microalgae meal as FM/FO substitute for both the wind energy, as well as the national grid energy mix. It was lowest for the reference diet, similarly to the feed formulations that used guar meal as non-GMO SBM substitute (Figure 5.14, right).

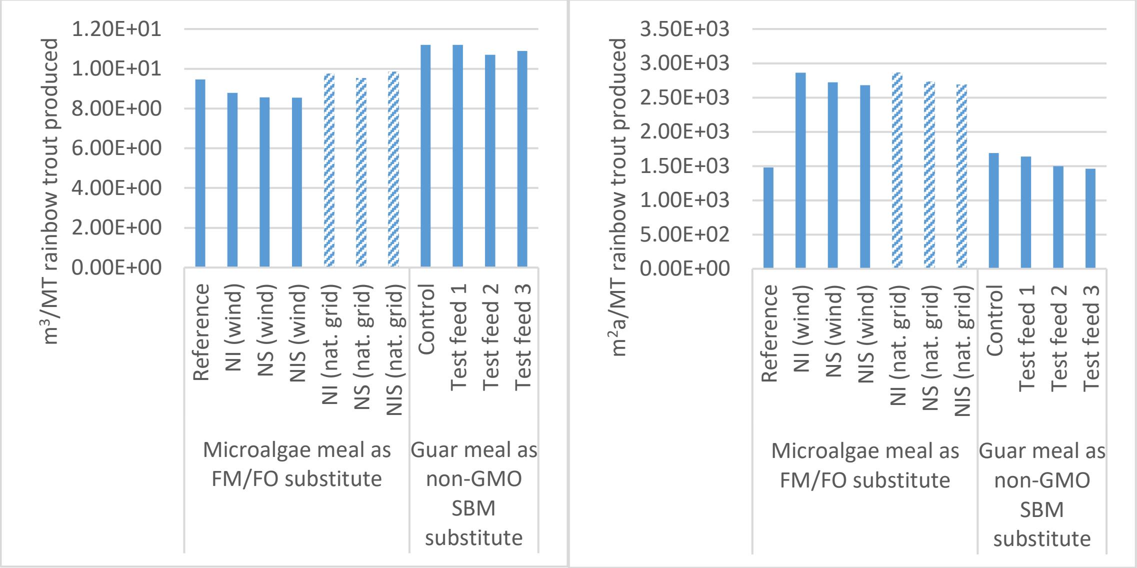


Figure 5.14: Blue water use (left) and land use (right) of the selected feed formulations. The patterned light colour bar is a sensitivity analysis, substituting wind energy with a national grid energy mix at farm level.

The feed formulations with guar meal as non-GMO SBM substitute (incl. control) show the highest embodied fish values of approx. 800 kg/MT. The feed formulations that used microalgae meal substituted FM and FO completely (excl. reference) (Figure 5.15).

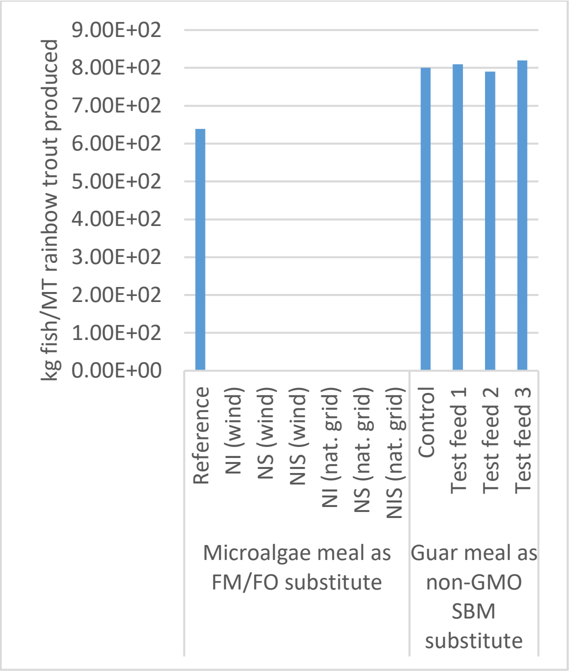


Figure 5.15: Embodied fish of the selected feed formulations.

5.4 Discussion

Our results showed that although inclusions of microalgae meal and guar meal are low (max 12.6-15%, respectively), the relatively low environmental costs of producing guar meal and algae meal are reflected in some LCA impact categories of the diets used to raise fish. While the feed formulation itself is responsible for most of the environmental impact (Bohnes *et al.*, 2018), the actual performance in terms of feed conversion ratio (FCR) is more favourable for diets containing guar meal (average 0.795, σ 0.01291 (Pach and Nagel, 2018)) compared to those in which microalgae meal was used (average 0.975, σ 0.037859 (Sarker *et al.*, 2020)). The FCR is the ratio of feed fed to weight gain and can be lower than 1 if the weight gain (wet weight) of the fish is compared with the feed input (dry weight) (Traifalgar, 2019), especially in this case where juvenile rainbow trout was used for both experiments by Sarker *et al.* (2020) and Pach & Nagel (2018).

In the following paragraphs the environmental performance of guar meal and microalgae meal are compared (FU: 1 MT of feed ingredient produced) with the other ingredients and discussed in relation to the available literature. This is followed up by an overall analysis of the environmental performance of the feed formulations compared with the literature. More specifically, the feed formulation was compared on a FU of "1 MT LW rainbow trout produced", to take the feed performance (FCR) of the different feed formulations at the farm into account. For future analysis it is important to assess the nutritional performance of both ingredients in independent feed trials. The origin of both guar as well as microalgae, as well as the presence of e.g., ANFs, might affect the nutritional value and therefore the performance in the diet.

Microalgae meal

Microalgae meal can be produced in a variety of systems with different nutritional and environmental implications. As highlighted in the study of Maiolo *et al.* (2020b), most of the impacts of microalgae (*Tetraselmis suecica* and *Tisochrysis lutea*) production in photobioreactors are related to energy consumption and the nutrients provided as a carbon source and fertilizer. In terms of energy consumption, impacts could differ depending on the production country and respective energy mix (Maiolo *et al.*, 2020b). Additionally, Maiolo *et al.* (2020b) focussed on two production systems with intensive microalgae production in photobioreactor circulation systems, while the assessment includes an extensive pond farm producing a mixture of diatom species. The study of Maiolo *et al.* (2020b) also used economic allocation in the second scenario, but their functional unit was different as they focussed on 1 MT of protein contained in the meal.

Microalgae meals harvested from open ponds showed low impact in most categories. However, the CEU for microalgae meal produced with wind energy at the farm was the third highest value compared to the other ingredients assessed. However, approx. 90% of the CEU originated from renewable energy (wind) and therefore resulting in a low GWP. However, the highest CEU value was for microalgae meal produced at the farm with the national energy grid mix of country (confidential) as part of the sensitivity analysis, which resulted in a much higher GWP, the second largest value after soybean protein concentrate. This demonstrates that location and access to renewable energy is a key factor in the sustainability of many feed ingredients. While the drying of the algae is associated with high energy use and contributes to the largest impact in most categories (except land use), it also results in the production of freshwater and therefore a negative value for BWU in an area where freshwater is scarce. However, the freshwater requirements to produce non-renewable energy used within the national energy mix negates those gains if grid electricity is used, as a result of the high inclusion of hard coal, natural gas and oil (IEA, 2017). This clearly shows the importance of taking the local context into account when interpreting results. As mentioned in the PEFCR "*Feed for food producing animals*" EU (2018b), not all impact assessment methods are equally robust, including various impacts at the local level. In relation to the analysis, a nutritional product is produced on what is considered non-productive land, while producing freshwater in the process, which is highly valuable in an arid region. This is important to consider in relation to the water-energy-food nexus, indicating opportunities for the water, energy, and food sectors to align policies and arrangements benefiting resource use and sustainability in the area (Weitz *et al.*, 2017).

Guar meal

This analysis showed the importance of guar meal as a low impact ingredient across most impact categories assessed in this analysis. The low impact is mostly associated with the extensive agricultural production practices of guar seeds. However, the application of economic allocation as a methodological LCA choice at the processing stage also plays an important role assigning relatively more impact towards high value guar gum, rather than relatively lower value guar meal, which is considered a by-product. A relatively lower economic value results in a relatively lower environmental footprint and therefore sustainability incentives to use low value by-products, according to the study of Regueiro *et al.* (2021). The high demand for guar gum is mainly driven by the oil and gas industry and this is expected to grow. If the demand for guar gum (and therefore the revenue, which consist of co-product yield and price) would go up over time, the proportionate value of guar meal and therefore its impact will likely decrease. Consequently, resulting in a variable environmental impact, depending on time and price action between the two co-products because of supply and demand. These shortcomings of using economic allocation were also highlighted by the study of Pelletier & Tyedmers (2011). However, applying long term average prices can reduce the volatility (Guinée *et al.*, 2002), but such data was not obtainable at the time of this analysis. In addition, it is important to consider the ethical implications of using guar meal in relation to the driving factors behind the production of this co-product. It has a relatively low environmental impact because of the application of economic allocation at the guar seed processing stage. Essentially, guar meal is a relatively low value co-product compared to the high value guar gum which production is mainly driven by the demand for applications in the oil and gas industry. Nevertheless, Pelletier and Tyedmers (2011) argue that economic allocation could give the illusion that environmental impact has changed over time, while in reality the actual supply chain has not changed and the perceived changes in impact are due to market preferences. While this is applicable to the relative environmental impact between guar meal and guar gum, the actual agricultural supply chain to produce guar seeds showed a relatively low environmental impact compared to e.g., soybean and its derived ingredients.

Conventional ingredients used in European aquafeed

The impact associated with the other terrestrial and marine ingredients assessed in this analysis varies significantly. The environmental impact per MT of ingredient provides a better understanding of their relative contribution to the overall impact of aquafeeds. This enables a better understanding and interpretation of the environmental impact results of the feed formulations, highlighting the environmental "hot spots" and the potential candidates for further research on substitution. Terrestrial ingredients, such as soybean derived ingredients (soybean protein concentrate and meal), wheat gluten and rapeseed oil show the highest impact in most categories. This can be explained by the resources required in the agricultural process as well as the processing of the crop into various ingredients. As mentioned in the study of Pelletier *et al.* (2009) rapeseed oil and wheat gluten meal are more intensive in resource use and associated emissions compared to most efficient marine ingredients (e.g. menhaden meal and oil). However, it is worth mentioning that the allocation choice for co-product outputs in Pelletier *et al.* (2009) was gross chemical energy content. Environmental impact results could vary significantly based on the allocation choice, and therefore the interpretation of studies using different allocation methods is complicated (Henriksson *et al.*, 2012; Avadí *et al.*, 2018). According to Silva *et al.* (2017), who applied mass allocation, to obtain lipid ingredients (e.g., FO and rapeseed oil), more volume of the source ingredient is required resulting in higher impact of fats compared to meals. The study of Newton *et al.* (2022) clearly showed the higher GWP of soybean derived ingredients and wheat gluten meal compared to most marine ingredients. In addition, when GWP LUC is considered, soybean protein concentrate showed significantly higher values compared to the rest of the ingredients assessed in the study of Newton *et al.* (2022). Land use change is a major driver of GHG emissions, but there is much uncertainty around the proportion of GHG emissions originating from this activity (Jia *et al.*, 2022).

Marine ingredients had relatively higher impacts in the OLD, AP and BWU categories compared to GWP. These higher impacts are mostly associated with the high energy (fuel) use for fishing, as well as from the processing stage of rendering into FM and FO (Newton *et al.*, 2022). Fish by-products showed a relatively low environmental impact compared to whole fish (Newton *et al.*, 2022), and therefore considered an appropriate strategy to reduce environmental impact. This is line with our impact results for embodied fish, showing lower values for FM and FO in the industry mix (incl. by-products) compared to FM and FO originating from whole fish. This is in line with the findings in the study of Kok *et al.* (2020) and Regueiro *et al.* (2021) showing that fish by-products inclusion in FM and FO production is a viable strategy to reduce embodied fish in the overall diet, as well as the values for most other impact categories, especially if economic allocation is applied (Regueiro *et al.*, 2021; Kok *et al.*, 2020).

Environmental performance of the feed formulations

The environmental performance of the feed formulations by Sarker *et al.* (2020) and Pach & Nagel (2018) are differently affected by the substitution of FM/FO and non-GMO SBM with microalgae meal and guar meal, respectively.

The fish use embodied in FM and FO was substituted completely in the microalgae meal diets in the feed trial of Sarker *et al.* (2020). Consequently, part of the water use associated with FM/FO production was negated by the freshwater production associated with microalgae meal production, explaining the decline in freshwater use (BWU). However, in the sensitivity analysis for the microalgae diet, the freshwater use increased because of the water needed to produce non-renewable energy. LU declined for the guar meal diets, because of the lower land use for guar meal compared to soybean meal. However, it increased significantly for the microalgae meal diets, because of the higher inclusions of rapeseed oil (between 11-13%) compared to the reference diet (0% rapeseed oil).

In terms of the CEU, the diets in both trials showed a similar non-renewable energy use, while the renewable energy use is slightly higher for the diets including microalgae meal. However, in terms of non-renewable energy use, this is much higher in the sensitivity analysis where wind energy was replaced with the national grid energy for microalgae meal production. The results of the CEU are reflected in the GWP results, showing similar values for the diets in both feed trials, but with higher values for the sensitivity analysis. However, the GWP LUC is significantly higher for all the microalgae meal diets (incl. reference diet) including sensitivity analysis because of the high inclusion levels of soy protein concentrate (20%) and rapeseed oil (0, 13, 12 and 11%) in the diets in the study of Sarker *et al.* (2020) (Table 5.1). The study of Maiolo *et al.* (2020a) assessed the environmental impact of 1 MT of rainbow trout produced at farm gate in different Italian farms. The weighted average CEU values in Maiolo *et al.* (2020a) were almost three times higher compared to this analysis. In the analysis of Maiolo *et al.* (2020a), approx. 75% of the energy demand comes from aquafeed, in which plant and other animal ingredients consume most energy. The exact diet formulations in Maiolo *et al.* (2020a) are not provided and environmental impact could differ significantly depending on the origin and their processing of ingredients. The GWP value is relatively similar for the microalgae meal diets, but about half for the guar meal diets compared to the weighted average value of three farm types in the study of Maiolo *et al.* (2020a). However, the higher levels of GWP in this analysis for the microalgae diets are mostly related to LUC, and it is unclear if this was taken into account in the study of Maiolo *et al.* (2020a). Nevertheless, the GWP LUC values for the microalgae meal diets (incl. reference) are approx. half of the values mentioned for farmed trout in the paper of Gephart *et al.* (2021), which includes LUC defined as “conversion of natural areas”. However, it must be noted that the results of Gephart *et al.* (2021) use an FU of edible yield, while also mass allocation was applied (Gephart *et al.*, 2021).

The AP and EP in this analysis show values half of those mentioned in study of Maiolo *et al.* (2020a). The same arguments as previously stated could be the explanation for the differences in values, while in addition, the ReCiPe 2016 (H) V1.02 method (Huijbregts *et al.*, 2016) used in the study of Maiolo *et al.* (2020a), compared with the CML-IA (baseline) (2016), could lead to discrepancies. Other factors that could play a role are the farm conditions (e.g., river vs well water), different feed ingredients and the effect on the FCR.

Allocation choice

An additional uncertainty is the allocation choice, such as economic and mass allocation, which could cause a huge variability in the environmental impact results (Henriksson *et al.*, 2012; Avadí *et al.*, 2018). The use of land and freshwater to produce trout is mostly related to feed use. Interestingly, according to the study of Gephart *et al.* (2021), trout diets have relatively fewer crop ingredients, combined with a high edible yield and low FCR resulting in the lowest freshwater use for all the species assessed. Nevertheless, land use in this thesis is approx. half of that reported by Gephart *et al.* (2021). Additionally, freshwater use (BWU) in this thesis is significantly lower (10m^3/MT) compared to the approx. 150 m^3/MT mentioned for trout in the study of Gephart *et al.* (2021) and the 130 m^3/MT for salmon by Newton and Little (2018). Lower land use values could be explained by a different functional unit for 1 MT of trout (LW vs edible weight) and the mass allocation method as used by Gephart *et al.* (2021). Nevertheless, Newton & Little (2018) also used economic allocation, but only at the primary processing stage, while the analysis in this thesis didn’t apply processing, but attributed the environmental impacts to 1 MT of LW rainbow trout. Nevertheless, this cannot explain the discrepancies in freshwater use. More specifically, while freshwater (BWU) results for marine ingredients are in line with the study of Newton *et al.* (2022), they differ significantly when crop ingredients are compared with available literature. According to Mekonnen & Hoekstra (2011), the global average blue water (BWU) footprint in m^3/ton for wheat gluten meal (785), soybean meal (83) and rapeseed oil (438) is significantly higher than 8.53, 8.01 and 4.48 m^3/ton calculated in this analysis, respectively. Despite the uncertainties and assumptions in the study of Mekonnen & Hoekstra (2011), such as the type of soil, resolution, limited info on irrigation maps and fertilizer applications for most crops, share of green, blue, and grey water consumption, their study results showed overlap with other studies mentioned in their discussion. Therefore, the discrepancies in this analysis might be explained by inconsistencies in the available LCIs for crop ingredients in the database in Agri-footprint (2022) and Ecoinvent (2022). More specifically, if data on blue water is not available, but green water is, the model assumes blue water use to be 0 m^3/ton. Another explanation could be the large regional spread, as the blue water footprint varies significantly per country, e.g., while the average global value for soybeans is 70 m^3/t, 25% of countries have a footprint of 6.2 m^3/t or lower (Blonk, 2023). Another explanation could be the water correction ratio, as Agri-footprint models water consumption, but not water withdrawal itself, as on average the ratio between water withdrawn and consumed water is approx. 0.44 for all countries but can be as low as 0.16. Conclusively, the ReCiPe result and Mekonnen & Hoekstra are not comparable (Blonk, 2023).

A balanced basket of feed ingredients

This analysis showed clearly that the guar meal diets have the lowest environmental impact for most categories. However, the microalgae meal diets showed a higher total non-renewable and renewable CUE, but values were similar to the guar meal diets if only non-renewables were considered. Similar values as the guar meal diets are also observed for GWP. However, GWP LUC for the microalgae meal diets is significantly higher because of the inclusion of soybean protein concentrate. Overall, OLD, AP and BWU are lower for most microalgae diets. Nevertheless, while FM and FO are substituted with microalgae meal, rapeseed content increased to meet nutritional demands. Significant trade-offs have been observed in the microalgae meal diets, for EP and LU related to the increasing inclusion of rapeseed oil. Conclusively, terrestrial ingredients, such as soybean derived ingredients (soybean protein concentrate and meal), wheat gluten and rapeseed oil show the highest values for most impact categories. It is therefore important to balance these ingredients well and only include the minimum amount necessary to meet nutritional requirements of the farmed animal to balance resource trade-offs as best as possible.

5.5 Conclusion

Our analysis showed that the LCA impact categories are differently affected by the substitution of FM/FO and non-GMO SBM with microalgae meal and guar meal, respectively. To meet nutritional demand, other ingredients are also included, which leads to (unexpected) trade-offs. It is therefore crucial to identify ingredients with high values in most impact categories, such as soybean derived ingredients (soybean protein concentrate and meal), wheat gluten and rapeseed oil, and minimize their inclusion, while balancing with other ingredients to meet nutritional requirements of the farmed fish. By-products with low economic value should be prioritised for inclusion, which could favour the environmental outcome if economic allocation is used in the assessment method. This is an important consideration for low value guar meal, which is considered a by-product from the processing of relatively low impact guar seeds into high value guar gum, driven by increasing demand from the oil and gas industry.

Environmental performance is variable between and within ingredients, depending on the production system used. In the case of microalgae, our analysis showed a low environmental impact for the production in open ponds, especially when renewable energy was used. However, environmental impact could be much higher if the microalgae was produced in energy intensive photobioreactors, in a country with a high inclusion of non-renewables in the national energy grid mix, as shown by Maiolo *et al.* (2020b). While the algae in the open ponds also showed a relatively high CEU compared to the other feed ingredients, this is not reflected in the other environmental impacts results when renewable energy is used. Interestingly, the drying of the algae is considered the most energy intensive process, but also results in freshwater production (therefore negative values) when renewable energy is used. Contrary, if non-renewable energy were used, freshwater production at the farm would have been neutralised by the demand for freshwater to produce non-renewable energy elsewhere. Consequently, indicating the importance of on-farm access to renewable energy, especially in countries where non-renewables dominate the national energy grid mix, to produce feed ingredients with lower environmental impacts.

A sustainable feed formulation takes the price of the ingredients, nutritional value, and the environmental footprint into account. The footprint should be expanded with socio-economic indicators to cover the potential trade-offs that could occur. The aquaculture industry could benefit from a feed formulation strategy taking these aspects into account. This would enable the aquafeed industry to contribute responsibly to food security and the economy, balancing profitability, nutrition, and environmental sustainability. This would enable the aquaculture industry to produce more sustainable and nutritious seafood.

CHAPTER 6: SUSTAINABILITY MESSAGING ON A GLOBAL SEAFOOD TRADE LEVEL

Reference in text to the Supplementary Information (SI) is available online (Malcorps *et al.*, 2021a).

6.1 Introduction

Global seafood apparent consumption per capita increased from 9.96 kg in 1961 (FAO, 2020g) to 20.50 kg in 2018 (FAO, 2020f). The demand for high-value species such as salmonids, shrimps and prawns has shown some of the greatest growth as a result of the growing appetite in OECD countries and also rising income levels and urbanisation fueling demand in emerging markets (FAO, 2018). New players emerged in global trade, with significant global influence such as Thailand and China, while exports from South America and Asia have also increased (Gephart and Pace, 2015). Capture fisheries and aquaculture produced 179 million tons in 2018 with an estimated value of USD 401 billion, from which aquaculture produced 82 million tons at a value of USD 250 billion (FAO, 2020f). China and the rest of Asia are the largest seafood producers with a market share of 34% and 35%, respectively (FAO, 2020f). Europe (EU-28) represents one of the largest markets for seafood products and is highly dependent on imports to the EU market (STECF, 2018; EUMOFA, 2018a), as domestic production from local (EU member states) capture fisheries and aquaculture produces only 28% and 9% of the EU supply (14.61 million MT, LWE) in 2017, respectively (EUMOFA, 2019a). Seafood was most commonly imported from Norway, representing more than one-quarter of seafood products imported into the EU (EUMOFA, 2019a). The USA also shows a dependency on imports, estimates ranging from approx. 62% up to 90% of domestic supply. This could be partly explained by the complex supply chains and the role of important seafood trading partners such as China, importing a third of US seafood exports from which a proportion is shipped back to the USA after being processed (Gephart, Froehlich and Branch, 2019). Europe and North America produce a relatively small proportion of global seafood, but they account for approx. 63% of the global certified seafood destined for retail markets. In contrast, Asia which produces 69% of the global seafood supply, accounts for only 11% of global certified seafood production (Potts *et al.*, 2016).

The global seafood trade is not only driven by consumer demands and lead firms but is highly affected by the multi-polarity between producing and consuming regions and their respective cultural values (Bush *et al.*, 2019). The diversity of culture and economic status indicates different values and qualities perceptions between the major producers and consumers in the Global South and North, respectively (Little *et al.*, 2018; Bush *et al.*, 2019; Pieterse, 2017). While China is a key player in global production, consumption and trade of seafood (Crona *et al.*, 2020), it is also the largest aquaculture producer in the world in terms of volume (Newton *et al.*, 2021a). Additionally, an increasingly large proportion of seafood is imported into China, which creates a diverse market for Chinese and global stakeholders (Fabinyi *et al.*, 2016). Chinese exports of diversified products indicate an economic opportunity, but the sustainability criteria could be challenging (Fabinyi *et al.*, 2016). Alternative markets (e.g., eco-certification) in the Global North and emerging Southern domestic seafood markets align with differing consumer perceptions and demands (Little *et al.*, 2018; Mialhea *et al.*, 2018; Bush *et al.*, 2019).

Concerns about the sustainability of seafood production has led to the introduction of ecolabels in an effort to reward good practices with price premiums, while producers exhibiting bad practices could be excluded from more lucrative markets (Barclay and Miller, 2018; Tlusty, 2012; Ward and Phillips, 2008). Ecolabels fulfil an important role to guide consumers and the general public to make sustainability choices (Osmundsen *et al.*, 2020). However, sustainability certification is largely focused on capture fisheries with 80% of certified seafood being wild catch. The historical dominance of wild catch certification over aquaculture certification can be explained by rising awareness in Western markets of declining wild fish stock levels (Potts *et al.*, 2016), and concerns related to the illegal, unreported and unregulated fishing (IUU) and associated socio-economic and environmental impacts (Pramod *et al.*, 2014). Such issues led to the introduction of the Marine Stewardship Council (MSC) in 1997 (Christian *et al.*, 2013; Sutton, 1996), which is more recognized in the US and Europe compared to other continents where environmental awareness is now increasing and similar labels are being introduced (Gutierrez and Thornton, 2014; Jacquet and Pauly, 2007; Fabinyi, 2011; Hanson *et al.*, 2011; Xu *et al.*, 2012).

Over the last decade, certified aquaculture production has grown twice as fast as certified wild catch (Potts *et al.*, 2016). The relative growth of aquaculture production certification is reflected by supply constraints and a growing importance of aquaculture production to fulfil global demand for seafood (Potts *et al.*, 2016). Examples of widespread aquaculture certification schemes are the Global Good Agricultural Practices (GlobalG.A.P.) committed to good agriculture, livestock and aquaculture farm practices, Best Aquaculture Practices (BAP) developed by the Global Aquaculture Alliance (GAA) promoting responsible practices across farms, feed mills, hatcheries and processing facilities, and the Aquaculture Stewardship Council (ASC) aiming to determine adequate environmental sustainability and to raise the global standards of responsible aquaculture (Nhu *et al.*, 2016). Nevertheless, literature indicates that Chinese governance, traders and consumers have a greater emphasis on food safety, traceability, quality and freshness, rather than environmental sustainability (Fabinyi and Liu, 2016). This is evidenced by national labelling programs that often are not as rigorous as the global (voluntary) programs (Tlusty, Thompson and Tausig, 2016). Additionally, a systematic review by Carlucci *et al. (2015)* on consumer purchasing behavior in developed countries indicates variability of perceptions towards seafood production, consumption and attitudes towards food safety, product form and sustainability. More specifically, country of origin, production method, preservation method, packaging, product innovation and eco-labelling are considered most relevant in affecting consumers' choices. Carlucci *et al.* (2015) highlighted that fish and seafood is still mainly sold unbranded and unlabeled, but that it would be interesting to investigate the impact of sustainability, health, and nutritional claims on consumer behavior. Nevertheless, it is relatively unknown to what extent this has been influenced or picked up by the global seafood traders. A better understanding of consumer preferences and alignment of trade messaging strategies would facilitate trade between stakeholders. The importance of seafood as a globally traded commodity has led to international trade shows being crucial to the initiation and maintenance of business relationships. Such seafood shows are fora for agents of both producers and consumers, and locations where communication, in time and space, is intense and business deals brokered. Communicating product qualities from a standardized seafood exhibitor booth is necessarily constrained, and we hypothesized a study of logos and words would inform understanding of key communication strategies. We visited five international seafood shows (USA (Boston), Belgium (Brussels) and China (Guangzhou, Qingdao, and Shanghai)) and reviewed messaging displayed on the booths for terms specific to sustainability, health, and food safety. Given the global trade in seafood, one would expect there to be no difference in messaging across the different shows (null hypothesis). Alternatively, if there are regional differences in the importance of sustainability, health, and safety, then differences in messaging should appear across the different shows.

6.2 Seafood business-to-business trade level

6.2.1 Methods

In this study, a cross-sectional survey was conducted at five seafood shows in the major producing and consuming regions to gain understanding in the type of business-to-business messaging and virtue signaling by seafood traders on a global level. Specific data was collected to gain an understanding of the main messaging strategies, namely the type of logos and words used by different exhibitor booths from Africa, Asia, China, Europe (geographical), Latin America (LA), North America (NA) and Oceania.

Survey design

The target population were seafood exhibitor booths at business-to-business seafood shows in the USA (Boston), Belgium (Brussels) and China (Guangzhou, Qingdao, and Shanghai) (Table 6.1) in 2019. The details of the study population (companies represented by exhibitor booth(s)) were obtained from the website of the seafood show event. Exhibitor booths active in e.g., logistics and processing equipment were excluded from the list since their messaging strategy is focused on themes other than seafood sales or purchases, such as processing efficiency. The sample size was calculated based on the assumption that 50% of the exhibitors were using the type of messaging in the form of logos and words with 95% confidence level and 8% accepted error (precision) (CRS, 2019). The population was then stratified by country, then using Probability Proportion to Size (PPS) and simple random sampling.

Table 6.1: Surveyed booths.

Seafood show[1]	**Date (2019)**	**Exhibitor booths continent/area surveyed[2]**	**Total exhibitor booths (population)**	**Exhibitor booths surveyed (actual sample)**	**Author conducting sampling**
Boston	17-19 March	Asia (10) China (14) Europe[3] (9) LA (10) NA (185)	1,329	229	MT
Brussels	7-9 May	Africa (12) Asia (39) China (29) Europe[3] (116) LA (11) NA (20)	1,946	227	WM & SM
Guangzhou	23-25 Aug	Asia (15) China (89)	658	117	CZ
Qingdao	30 Oct – 1 Nov	Asia (17) China (200) Europe[3] (24) NA (8)	1579	261	WZ & RN
Shanghai	28-30 Aug	Asia (12) China (129)	2029	150	WZ

[1] The shows in Boston and Brussels were organized by Diversified Communications (Diversified, 2019). The shows in Guangzhou (CHINAFISHEX, 2019), Qingdao (CFSE, 2019) and Shanghai (WorldSeafoodShanghai, 2019) were organized by individual organizations.

[2] All booth nationalities with 6 or less booths at a show were sampled and included in the seafood show total, but excluded from the analysis on a continent/area resolution due to small sample size: Boston (Oceania (1)); Guangzhou (Africa (2), Europe (2), LA (6), NA (1), Oceania (2)); Qingdao (LA (6), Oceania (6)); Shanghai (Europe (4), LA (3), NA (1), Oceania (1)).

[3] Europe (geographical)

The survey tool was developed in the English language and was piloted at the Boston seafood show then optimised for Brussels. It was then translated to Chinese by WZ and CZ for use at the Guangzhou, Qingdao and Shanghai seafood shows. This was a passive survey in that the data collected were from text and logos observed on the exhibitor booths. Direct observation of human activity is a necessary and important methodology in marketing research, according to Lee and Broderick (Lee and Broderick, 2007). The motivation for an observational research method was (1) practical – interview with salespeople at such busy shows is unproductive, (2) cultural – neutral and consistent method for the observational researcher with different cultural backgrounds assessing booths from different nationalities at different shows, (3) scope – the sales booth is designed by the company or third party to position itself in the market and communicate their values. Employees at the booths were not asked any direct questions during the collection of these data. The following data were collected; country of origin, companies' activities, followed by observations of booth contents aimed at identifying messaging in the form of logos and/or words on the exhibitor booths. More specifically, the focus was on messages related to sustainability (socio-economic and environmental spectrum), quality, health characteristics, food safety, and provenance of the product (Supplementary Info (SI) Data – 5 Seafood Shows). It is important to note that all the messaging strategies (logos and words) from the sampled booths were noted, but it was not possible by visual observation to verify their veracity. In other terms, exhibitors were not asked whether their logos and words were supported by certification or not. This also accounts for the use of certain advertising words, which could be restricted by e.g., China's Advertising Law, prohibiting superlatives, false and misleading content (MOFCOM, 1994). In these cases, the display of certain logos and words is often due to the needs of specific buyers to use them, while their absence is generally due to policy restrictions. The causes of this possible non-conformity between message and actual certification have not been investigated, but we only recorded what was displayed.

Resolutions

Data were collected on a country level and converted to a continent/area level. In this case all countries were categorized under the major continents/areas e.g., Africa, Asia, Europe (geographical), Latin America (LA), North America (NA) and Oceania. China was categorized separately (not included in "Asia"), because of its large seafood production and associated international trade. Hong Kong was included in China, as it is an administrative region of China. However, Taiwan province of China (as defined in the FAO FishStatJ database) was considered Asia (FAO, 2020d).

Europe (geographical) covers the following peninsulas: mainland Europe, Scandinavia, Iberia, Italy, and the Balkans, including the European Union (EU) member states, European Economic Area (EEA) and the British Isles. Russia was considered Europe (geographical) because most Russians live in the Western side of Russia. Latin America (LA) was defined as all countries South of the USA, including Central America and South America.

Data cleaning and analysis

A high heterogeneity in message type was observed among seafood shows and exhibitor booths, therefore a consistent data cleaning was necessary to homogenize similarities and eliminate non relevant words and logos from the analysis (examples in SI Table S1 and S2). For instance, the use of a combination of words could differ per exhibitor booth, while the type of messaging is the same (e.g., no-chemicals and chemical free). Moreover, unknown acronyms or logos were deleted from the analysis, such as “SC” because the term was unknown and was not applicable to the non-American exhibitor booths. Any logo observed only once and of unknown meaning were removed. The words “fresh” and “delicious” were excluded from the analysis as they were not consistently assessed throughout the seafood shows, due to cultural differences between the researchers who surveyed the exhibitor booths. It was therefore important to gain understanding of the use and interpretation of these words, before observing them and including them in the analysis. For example, the term “fresh” is formed by two Chinese characters: xin (new) and xian (fresh) and seafood itself is also called 海 (hǎi: sea) 鲜 (xiān: fresh) in Mandarin. It is therefore no surprise to see that Chinese consumers use this term less on their exhibitor booths as freshness is already implied. Chinese consumers value “freshness” and prefer purchasing live fish, in contrast to e.g., North European consumers who often prefer more processed products. As a result, Chinese do not sell seafood as “fresh”, because seafood consumption is already associated with “freshness”. Comparing the use of these words across shows could therefore give a skewed interpretation of the results.

The exhibitor booths and recorded data (seafood show, country, continent, messaging, logos, and words) were organized in an excel sheet (Supplementary Info (SI) Data – 5 Seafood Shows). Pivot tables were used to calculate the proportion of the total number of exhibitor booths at each show using some form of messaging, logos, words, or both. This was followed up by an analysis into the use of specific logos and words on a seafood show and exhibitor booth continent/area level. In the case of the latter, results show the top 10 logos and words on a seafood show and exhibitor booth continent/area resolution.

Aggregated logo and word categories

Exhibitor booths use different messaging strategies and themes to target customers interested in product sustainability, quality, safety, health, social aspects and/or provenance. However, each exhibitor booth might use different quantities, types and themes of words and logos depending on its country of origin, location of the seafood show and nationality and product preferences of the customer. The categorization of the logos and words in aggregated groups provides insight in the type of "theme" messaging of the exhibitor booths across the different seafood shows.

The categorization into one or more themes was based on the available information on the website (main page or under "about") of the certifier/logo. The logos presented in the exhibitor booths were categorized in five themes: "Sustainability/Environment", "Quality", "Safety", "Health", and "Provenance", (SI Table S2). Most of the logos categorize perfectly under a single theme, except for a few which could be placed in several categories e.g., "Bureau Veritas. The major seafood certification labels (e.g., ASC, BAP and MSC) were considered a "sustainability" theme. The booth is the experimental unit, so there is no additional value to display more than one logo within the "sustainability" theme. In other words, if ASC was displayed on one exhibitor booth, and another exhibitor booth displayed the ASC and MSC logo together, both booths cover the "sustainability" theme. Words were categorized into six themes: Sustainability/Environment, Quality, Safety, Health, Provenance and Social (SI Table S3).

Statistics

Results were analyzed using Minitab® v18.1 statistical software package (Minitab Inc., Pennsylvania, USA). We used a chi-square test to explore if there is a significant difference in the frequency of a logo or word category between the five seafood shows (not between the exhibitor booth regions within a show). The frequency of each word and logo category (*sustainability/environment*, *quality,* and *safety*) were tested independently between the five seafood shows (SI Table S7).

6.2.2 Results

In total, we surveyed 984 exhibitor booths across five international seafood shows. In the following sections the results are presented and categorized under “Combination of Logo and Word Signaling”, and “Type of Messaging”.

Combination of logo and word signaling

Across all seafood trade shows (average), 16% of the exhibitor booths displayed both a logo and a word at the same time (Y/Y), while 49% had no messaging at all (N/N) (Figure 6.1). The remainder used either a logo or word, but not both. The average use of a combination of logos and words was relatively similar to the Brussels and Qingdao show, while Boston was at the higher end, and Shanghai at the lower end in terms of messaging in the form of logos and words. More specifically, Chinese exhibitor booths at Brussels, Guangzhou and Shanghai were least likely to display both logos as well as words. The results also indicate that a relatively small share of exhibitor booths in Boston neither used logos nor words (N/N) compared to the other seafood shows, where a N/N seems to be more common.

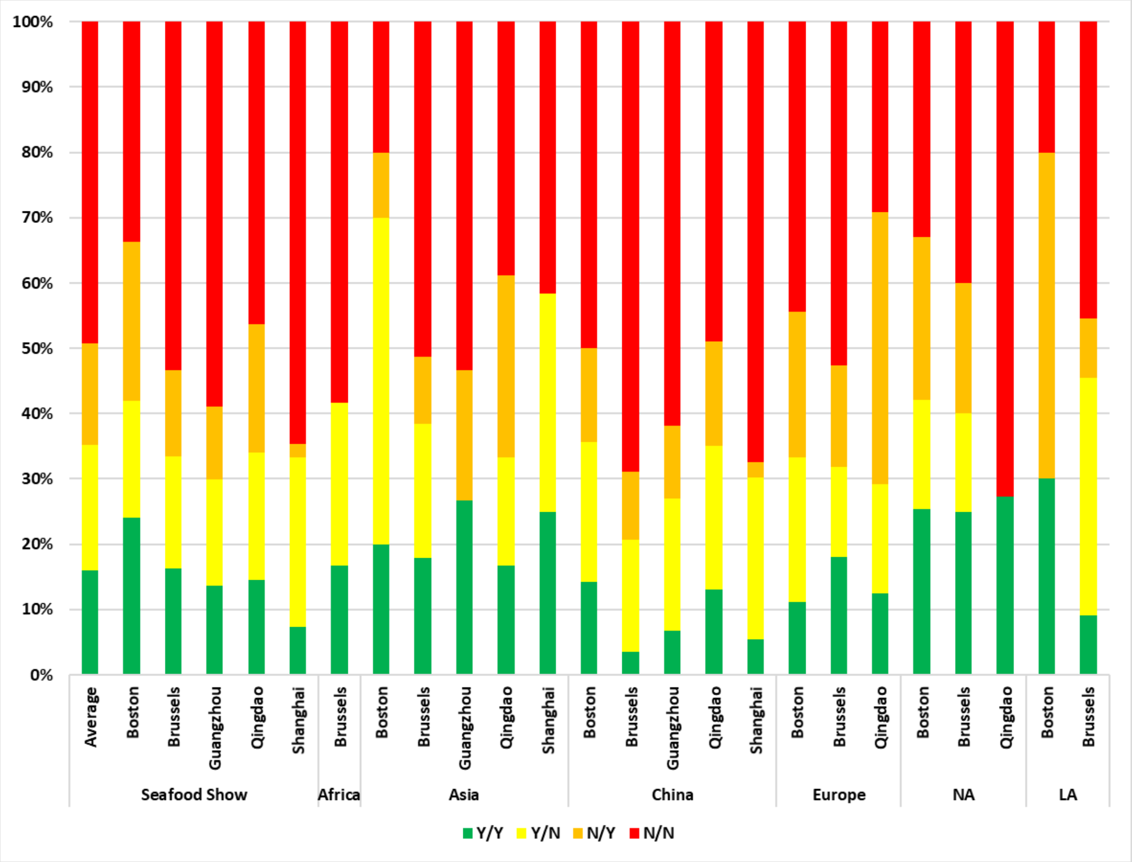


Figure 6.1: Proportion of exhibitor booths from different regions displaying (logo and word, Y=yes, N=no) at Boston, Brussels, Guangzhou, Qingdao, Shanghai seafood shows (N=984).

The results (Figure 6.1) indicate that overall messaging seems to be more present at the Boston seafood show compared to seafood shows in China. This trend is also observed by Chinese exhibitor booths across the seafood shows, showing relatively less messaging (especially Y/Y) compared with the average (all exhibitor booth nationalities combined) across the five seafood shows. Interestingly, Asian (excluding China) exhibitor booths at each of the five seafood shows had relatively similar values compared with the average of the five seafood shows (all exhibitor booth nationalities combined), while these values were relatively higher than the Chinese exhibitor booth across the five shows.

Exhibitor booth messaging through both logos and words was most present at the Boston seafood show. On an exhibitor booth continent/area resolution, the use of both logos and words was dominated by Asian exhibitor booth holders at the Guangzhou and Shanghai seafood show, NA exhibitor booth holders at Boston, Brussels and Qingdao seafood shows and LA exhibitor booth holders at the Boston show.

Type of messaging

The Sustainability/Environmental messages were more present at the Boston and Brussels shows than at the Chinese shows (Figure 6.2, SI Figure S6a). Across all shows, "sustainability" logos were more prevalent than "sustainability" words, with exception of Boston (LA), Brussels (NA) and Guangzhou (China). Overall, it seemed that Asian exhibitor booths exhibited relatively more "sustainability" category logos than words.

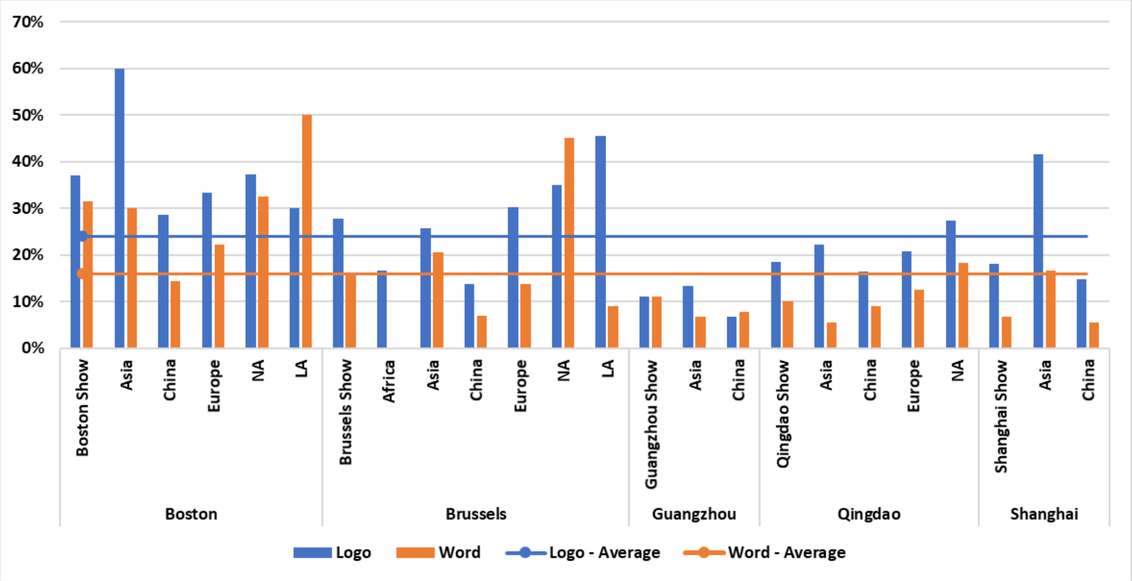


Figure 6.2: Percentage of exhibitor booths displaying "sustainability/environment" messaging at five international seafood shows (N=984).

We found that there was a significant difference between the use of “sustainability” logos and between “sustainability” words at the five seafood shows (Figure 6.2; DF=4, P<0.0001, SI Table S7). Overall, the use of “sustainability” logos (SI Table S4) was most commonly shown at the Boston and Brussels seafood shows. More specifically, “sustainability” logos, such as MSC were present on 11% of all exhibitor booths across the five seafood shows (average), followed up by BRC (“quality” logo) and HACCP (“safety” logo) at 11% and 10%, respectively. The MSC logo was shown on 17% and 14% of the exhibitor booths at Boston and Brussels shows, respectively. For the Brussels show the second most commonly shown logo was ASC (“sustainability” logo) present at 14% of the exhibitor booths, while the second most commonly shown logo at Boston was BAP (“sustainability” logo) (13%) with the ASC logo ranked 4th (7% of exhibitor booths).

A similar trend was observed with words such as “sustainability” (SI Table S5), which was shown at 21%, 10% of the exhibitor booths at the Boston and Brussels seafood shows. However, this was significantly different for most Chinese shows such as Guangzhou and Qingdao where the word “quality” was shown on 7% and 5% of the exhibitor booths, respectively. This also explains the presence of “quality” at 9% of all exhibitor booths across the five seafood shows (average), followed by words such as “sustainability” and “natural” at 8% and 6%, respectively.

There was a significant difference between the presence of “quality” words but not between logos (P<0.0001 and P>0.7209, respectively) at the five shows (Figure 6.3; DF=4). Asian and Chinese exhibitor booths across Boston and Brussels seafood shows were noted for a relatively high presence of the “quality” logo category, whereas for Asian exhibitor booths in Guangzhou and Qingdao, and European and NA exhibitor booths at Qingdao, the use of “quality” words compared to logos increased. Results indicate that European exhibitor booths use mostly words rather than logos to communicate about quality across seafood shows. The most common “quality” logo across the shows (average) was BRC (SI Table S4) and the word “quality” itself was also common across all shows (average) (SI Table S5).

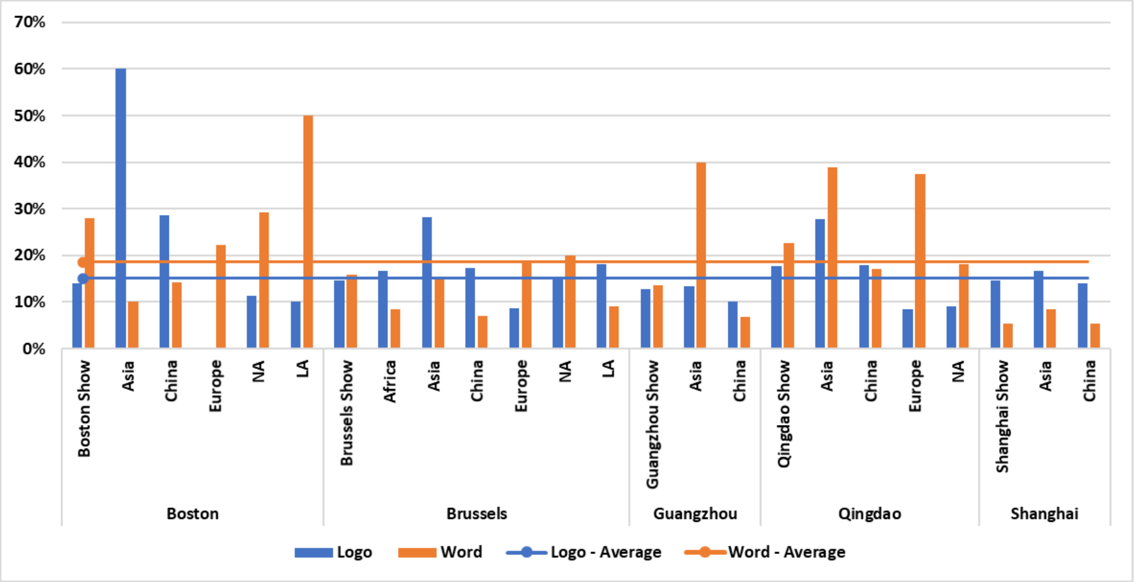


Figure 6.3: Proportion of exhibitor booths from different regions displaying "quality" wording or logos at five international seafood shows (N=984).

The frequency of logos and words related to "safety" was different between the five shows (Figure 6; DF=4, P<0.0001 and P<0.0101, respectively). Overall, the category "safety" was most commonly shown at the Chinese seafood shows and on Chinese and Asian exhibitor booths across all shows (Figure 6.4, SI Figure S6c). Interestingly, overall "safety" logos are more commonly shown compared to the category "safety" words. However, some exhibitor booths from NA, Europe and LA seem to use a more balanced presentation of words and logo categories. The top 3 logos include HACCP (13-20%) and ISO (9-11%) and these "safety" logos were most commonly shown at the Guangzhou, Qingdao and Shanghai seafood shows (SI Table S4). The word "safety" was less common, on 2% of the exhibitor booths across all five seafood shows combined (SI Table S5).

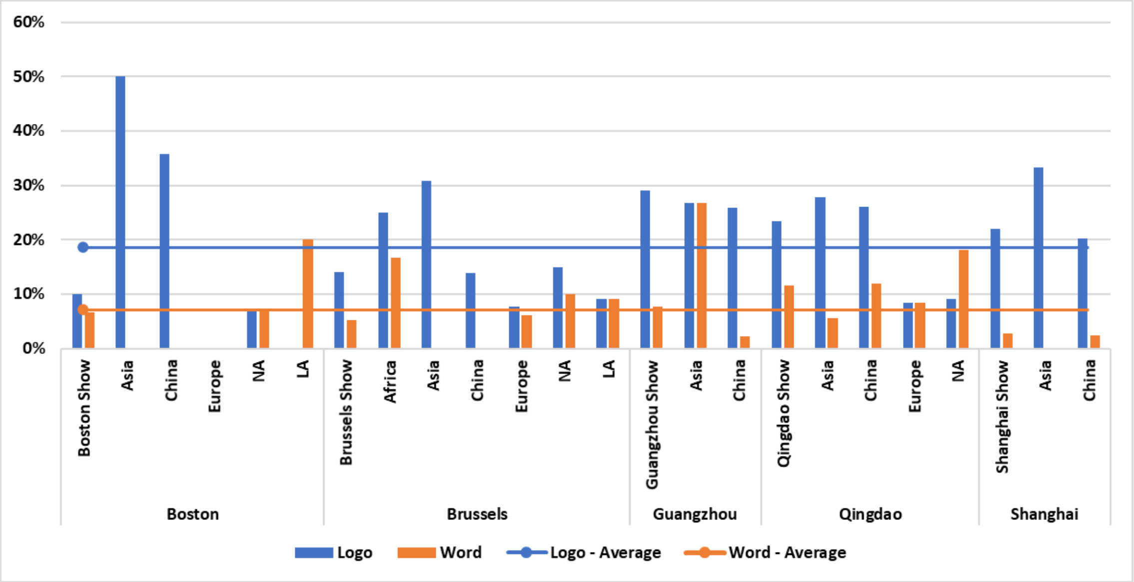


Figure 6.4: Proportion of exhibitor booths displaying "safety" wording or logos across five international seafood shows (N=984).

The following categories were less commonly present on the exhibitor booths and are therefore briefly discussed (graphs included in the SI Figure S6). The category "health" was dominated by words rather than logos (up to 1%), with a word presence between 10% and 13% for all shows, except for the Shanghai seafood show where the "health" category for words was present at approx. 4% of the exhibitor booths (SI Figure S6d). The logo category "provenance" was present between 1% and 8% of the booths, while the word category "provenance" was not present at most shows, except for up to 2% of exhibitor booths at Brussels and Qingdao (SI Figure S6e). The logo category "social" was not present at all, while words in this category were only present on approx. 6%, 3% and 2% of the exhibitor booths at the Boston, Brussels, and Qingdao show (SI Figure S6f).

6.3 Discussion

In 2019, across five seafood trade shows, close to half of the exhibitor booths did not use logos or words on the booths to signal characteristics of the products. Seafood traders from the major producing and consuming regions use different types of messaging at the seafood show where they exhibit.

The certification in the Global North is driven by lead firms in the form of large retailers and manufacturers (Potts *et al.*, 2016). These commercial entities who often function as a “choice editor” are guaranteeing and displaying a certain product quality or environmental standard through third party certification (Little *et al.*, 2018). Meanwhile, distribution in Asia is facilitated by a range of middle-sized regional retail companies, which requires certification for the whole supply chain, which is more costly (Tsantiris, Zheng and Chomo, 2018; Wakamatsu, 2014). In the context of aquaculture smallholders in the Global South, obtaining certification is complex, expensive and requires a certain level of managerial capability, often resulting in their exclusion from markets that require certification (Bush *et al.*, 2013).

In additional to ethical considerations to meet consumers demands, a recent study indicates that in the case of companies listed at the Oslo Seafood Index, sustainability reporting commitments to, for example, ASC, Global Salmon Initiative (GSI) and Global Reporting Standard (GRI) standards could have a positive effect on the market value of a company (Nygård, 2020). However, this does not always reflect sustainability performance, as companies in controversial industries seem to be more active in Corporate Social Responsibility (CSR) communication activities compared to companies in non-controversial industries (Kilian and Hennigs, 2014).

In general, European consumers show an interest in the environmental impact associated with aquaculture production or capture fisheries (Schlag and Ystgaard, 2013). From a global perspective, some consumers are willing to pay a premium for labelled, more sustainable products (Hynes, Ravagnan and Gjerstad, 2019; Lim, Hu and Jr., 2018; Bronnmann and Hoffmann, 2018), but this could differ depending on the product geographical origin (Lim, Hu and Jr., 2018) and type of product (wild-caught vs farmed) (Bronnmann and Hoffmann, 2018). Additionally, some consumers prefer seafood products from local retailers because of the perception that they are of higher quality (Bronnmann and Hoffmann, 2018). Nevertheless, interest in sustainability is reflected by the findings, showing common messaging of sustainability logos and words at the Boston and Brussels seafood shows. In contrast, the results indicate a relatively lower presence of sustainability messaging at Chinese seafood shows, perhaps suggesting its lower priority among consumers in Asia. The literature around relative interest in the environment and affluence are mixed. Whereas higher rates of individual affluence have been associated with higher rates of environmental concerns (Givens and Jorgenson, 2011; Nawrotzki, Guedes and Carmo, 2014), affluence on a national-level has been associated with lower levels of individual environmental concern (Givens and Jorgenson, 2011).

On an aquaculture or fishery certification level, MSC is commonly shown at the Boston and Brussels seafood show, while ASC is at the 4th and 2nd place, respectively (SI Table S4). In contrast, the Chinese seafood shows have a high presence of "safety" and "quality" logos on their exhibitor booths. The obvious emphasis on safety and quality seems to address the increasing concern of the public following well published food-related public health scandals. It was only in 2009 that China's first law to regulate food safety came into force (Li and Hope, 2021). The results of this study echo investigations that China is in the development phase of outlining (sea)food traceability processes, and further regulations and industry guidance are needed (Charlebois *et al.*, 2014; Qian *et al.*, 2020).

Most of the certification schemes focus on environmental health and governance (implementing environmental indicators) and show a minor focus on cultural and economic issues. This is also the result of the fact that sustainability as a concept is poorly defined and often used as a narrow interpretation (Béné *et al.*, 2019; Tlusty *et al.*, 2019; Tlusty and Thorsen, 2017). The incentives to buy sustainable seafood from the perspective of a e.g., UK customer is the strong moral obligation, pressure from family and friends and a positive attitude toward buying sustainable seafood (Honkanen and Young, 2015). While German consumers highlight the importance of the type of fish species, taste, country of origin and concerns about sustainability, which are relevant factors influencing purchase decisions (Hinkes and Schulze-Ehlers, 2018). This is also reflected the findings for words, as "sustainability" on exhibitor booths, which are commonly shown at the Boston, Brussels and Shanghai shows, while other "sustainability" words, such as "environment", "natural", "responsible", "no pollution" are less present on the exhibitor booths, but throughout the top 10 words across all seafood shows and are more related to environmental impact (SI Table S5). Nevertheless, sustainability is a journey, while it is often being marketed as a static point ("it is sustainable"), which limits further development through a lack of incentives (Tlusty *et al.*, 2012; Tlusty and Thorsen, 2017). Despite Osmundsen *et al.* (2020) concluding that certifications have narrow definitions of sustainability centering around the environment and governance, that many seafood traders still follow, perceptions of sustainability maybe changing as some certifying organizations broaden the indicators they use. Increasing evidence suggests that consumers and firms are more interested in improvements to production that positively impact ocean health (Tlusty *et al.*, 2019). This is reflected in the results for the seafood shows average and the Boston and Brussels seafood shows in particular where MSC is by far the most commonly shown logo on the exhibitor booths (SI Table S4).

Narrow narratives drive seafood production away from broader sustainability discussions within the food production system (Tlusty *et al.*, 2019) Aquaculture is increasingly dependent on both marine and terrestrial systems for feed ingredients, both having associated environmental impacts (Newton and Little, 2018; Malcorps *et al.*, 2019a; Zhang *et al.*, 2019; Naylor *et al.*, 2021), and it is therefore crucial to integrate aquaculture into the global food production system and broader sustainability discussions.

A certain segment of consumers showed a preference for wild products, which is reflected in the minor use of the word “wild” on the exhibitor booths at the Qingdao and Shanghai seafood show (SI Table S5). A survey among Chinese middle-class urban seafood consumers indicates that taste, nutrition and health are the most important motives to consume seafood, while wild seafood appears to be preferred over farmed, even if the consumer can’t tell the difference between them (Fabinyi *et al.*, 2016). A web-based survey by Wang and Somogyi (2020) on the motives for luxury seafood consumption among Chinese consumers indicated two dimensions of importance: food value and symbolic value. This study showed that 5 out of the 8 most important specific motives are closely related to nutrition and taste (“umami”, “delicious”, “fresh”, “like to eat”) and health (“high quality life”). Additionally, the study of Yunfeng (2020) found that health awareness was high in the coastal area of Dalian in China, and this was also an important driver for the seafood purchasing frequency of local Chinese consumers. The importance of health as a consumption driver was also reflected in this study for the word category “health”, which was present on the Chinese exhibitor booths at Guangzhou, Qingdao and Shanghai seafood shows. This is in line with the results for Boston and the Brussels seafood show, where this type of messaging was also present on some exhibitor booths (SI Figure S6d).

The increased exhibition of sustainability logos in Boston and Brussels may be in part a response to the perception among some people that farmed fish has negative environmental impact (Bronnmann and Hoffmann, 2018). This is also a common narrative towards offshore/marine aquaculture in the USA (Froehlich *et al.*, 2017), which could also be influenced by the generalization of other environmental disasters. Additionally, certain consumers have the perception that farmed fish is less healthy and has lower quality compared to wild caught fish (Claret *et al.*, 2014; Verbeke *et al.*, 2007), which can be explained by the consumers perception of an “artificial” product. This could be caused by the lack of available information on production practices (Claret *et al.*, 2014; Vanhonacker *et al.*, 2011; Altintzoglou *et al.*, 2010). Consequently, this perception could create incentives to pay a premium for wild caught fish (Bronnmann and Asche, 2017; Darko, Quagrainie and Chenyambuga, 2016; Bronnmann and Hoffmann, 2018; Davidson *et al.*, 2012; Ariji, 2010), shellfish and seaweed, especially in the coastal region where there is more awareness regarding certification and the origin of seafood (Brayden *et al.*, 2018). This clearly indicates a need to better understand the many reasons that drive seafood consumption and the importance of transparent communications around seafood products by means of information, programs and certifications (Murray, Wolff and Patterson, 2017; Bronnmann and Hoffmann, 2018).

The findings indicate that seafood shows in China show relatively less messaging including "sustainability" compared to the Boston and Brussels seafood show. However, Asian exhibitor booths at Boston and Shanghai show relatively more messaging in the category "sustainability" compared to the show average. Similarly, sustainability certification was not present in the top 3 logos of all three Chinese seafood shows, while it was widely in evidence at the Boston and Brussels seafood show (SI Table S4). This could be explained by consumer demand and the way seafood distribution, trade and certification schemes are organized. Distribution in Asia takes place in a range of middle-sized regional retail companies, which are often individually not certified, because of the associated costs and lack of benefits (Tsantiris, Zheng and Chomo, 2018; Wakamatsu, 2014). Additionally, in the case of Chinese consumers, less public interest is shown towards sustainable production as there is more emphasize on food safety (Fabinyi, 2016). Overall, this is also reflected by the results indicating less sustainability messaging at Chinese shows compared to the Brussels and Boston seafood show, while product safety and quality (indicated by HACCP, BRC and ISO in the top 3 logos, SI Table S4) is valued over environmental concerns. The logo and word category "safety" is commonly observed at Chinese shows (Guangzhou, Qingdao, and Shanghai) compared to the Boston and Brussels seafood shows (SI Figure S6c).

In China there is a strong connection between seafood and freshness and therefore quality and other associated positive attributes, partly due to the enduring popularity of "wet markets", a marketplace in which independent vendors sell fresh food including vegetables, meat, and fish. Product freshness is achieved as an outcome of the short supply chains connecting vendors to wholesalers, often facilitated by middleman (Zhong, Crang and Zeng, 2019). Chinese and other Asian vendors at international seafood trade shows may feel obliged to emphasize safety and quality aspects aligned with good health properties and naturalness because the freshness associated with wet markets is not so apparent. When it comes to fish consumption in China, there has been limited attention to freshwater fish consumption in the literature (Xian, 2016). Nevertheless, according to key informants in the study of Fang and Fabinyi (Fang and Fabinyi, 2021), freshness, but also food safety, quality, price and local culinary traditions were considered important influences on patterns of freshwater fish consumption in Chengdu fish market (Sichuan province, China).

Consumers are increasingly demanding clearly labelled, sustainable products, and it is therefore important for producers, processors, and traders to position themselves well by means of product differentiation to meet different demands of consumers, while taking sustainability aspects into account (Kumar, 2018; Bronnmann and Hoffmann, 2018; Brayden *et al.*, 2018). While the market for sustainable aquaculture products is relatively small, the study of Risius *et al.* (2019) emphasised the importance of providing information on production criteria for German consumers, e.g., production in natural ponds, practices and country of origin. Country of origin is reflected in the results by words such as “traceability”, which was in the top 10 of the Boston, Brussels, Qingdao, and Shanghai seafood show (SI Table S5). Additionally, overall, the messaging category “provenance” for logos was present at all five shows, but a relatively higher presence at the Chinese seafood shows (SI Table S6e). In China, the certification logo “*Product of Geographical Indication*” has been promoted with considerable subsidies to highlight product provenance for the (domestic) premium market (EP, 2020). It also follows the recent bilateral agreement on the Protection and Cooperation of the Geographical indication between China and the European Union (Li and Hope, 2021). This is relevant because of the importance of consumer decision making regarding the origin of the product, with a preference and willingness of some consumers to pay a premium for locally produced compared to imported products. In Germany, the highest importance was placed on “country of origin”, while sustainability claims and labels were considered positive but less important (Risius, Hamm and Janssen, 2019). Another study showed a preference for locally produced food over “organic food”, but this could vary depending on the consumers’ place of residence and product type (Hempel and Hamm, 2016). This could be explained by the fact that the market for sustainable aquaculture products is growing, but covers a relatively small market and is often less in demand by the mainstream consumer (Risius, Hamm and Janssen, 2019).

It is important to take cultural perceptions into account, as consumer attitudes towards seafood safety are often conflated with perceptions of sustainability, quality and traceability (Rahmaniya and Sekharan, 2018). Certain European consumer seems to be willing to pay more for “fresh” seafood compared to frozen seafood (Bronnmann and Asche, 2017; Ankamah-Yeboah *et al.*, 2019; Cantillo, Martín and Román, 2021). Additionally, while frozen seafood is commonly sold in most marketplaces, in some countries, such as China, fresh seafood is highly preferred, ideally purchased “live” compared to other product forms (e.g., frozen or canned) (Zhong, Crang and Zeng, 2019). Chinese consumers associate seafood already with “fresh”, as seafood itself is also called 海 (hǎi: sea) 鲜 (xiān: fresh) in Mandarin. The nature of this terminology excludes the need for messaging in this type. Conclusively, the interpretation of messaging and the use of it could differ from culture to culture.

In the case of consumers in the European Union, Cantillo *et al.* (2021) found that consumers who do not understand all the information provided on seafood products tend to consume less seafood. This indicates an opportunity to increase consumption by providing clearer information about the product. Such messaging, currently unusual, might lead on the benefits associated with seafood consumption, such as health benefits (e.g., contain little fat). Ensuring an optimal appearance of the seafood at point of sale and prominent use of brands and labelling would be part of such a strategy. Certification of quality, certification, origin of the product and associated socio-environmental impacts would also be important (Cantillo, Martín and Román, 2021). Currently certification focuses on eco-labels, which could be an important driver for increased consumption in the EU, who already demand compliance to presenting product information on labelling (Cantillo, Martín and Román, 2021). Such a strategy might also be suitable for other major markets such as the USA but unlikely to work in Asia at this stage due to cultural differences and the fact that a high proportion of seafood is sold unpackaged. A focus on food safety and quality, a well-managed cold chain, and the consumption of the whole fish would meet the cultural demands of the Asian consumer.

Study limitations and future research

The visual survey was conducted by researchers with a high proficiency level in the language used in the show. However, there are different cultural backgrounds regarding messaging and the way this is interpreted. This could influence the way data was written down during the visual survey and processed at a later stage. Additionally, certain logos and certification, such as FDA and HACCP are shown differently across seafood shows but are the same. However, HACCP is part of the FDA and is therefore assessed separately, mainly because FDA is USA specific.

The survey was conducted across five seafood shows in three countries in a single year, pre-pandemic. This means that the scope is limited to processed seafood, mainly marketed for the international trade and (long-distance) domestic trade requiring a long shelf life. However, in China a large proportion of seafood is still purchased in live forms in wet-markets (~60-80%), without packaging and not easy to label or ensure traceability, thus certifications are not easy to promote with these products. On the contrary, most of seafood in developed countries are imported processed forms, which are often labelled and traceable (Guan *et al.*, 2021; Peng *et al.*, 2020; Sun *et al.*, 2021).

The seafood shows are business-to-business orientated: the final consumer was not directly served at the show. This potentially affected the messaging strategy used by exhibitor booths, where messaging via packaging was not emphasised. Clearly sustainability messaging to final consumers would require systematic analysis of packaging, and is likely to reflect specific cultural norms and market conditions.

Preferences in the style and content of sustainability messaging used by actors will likely depend on their position within the seafood value chain. Therefore, for future research, an analysis of the type of value chain actor behind the exhibitor booths could provide more specific insights into the incentives to use certain types of logos and words. This could also include information on the number and size of the exhibitor booths that certain companies occupy. It is important to collect a consistent dataset across the seafood shows, which could potentially include the size of the company in terms of revenue and number of employees associated with the exhibitor booth(s), type of seafood sold in terms of species and origin (aquaculture versus wild) and product form (fresh versus frozen). This would add additional resolution to the current baseline where messaging has been compared across seafood shows.

6.4 Conclusion

Seafood is an important component in diets and is part of a complex trade network stretching across the globe. A variety of cultures show different perceptions towards the production and consumption of seafood. This analysis indicates a clear difference in messaging at business-to-business seafood shows between Global South (major producer in terms of volume) and Global North (major consumer in terms of monetary value). There is a clear difference between the focus on the product (e.g., quality and health aspects) and the production process (e.g., environmental sustainability and provenance). The Global North (Europe and the USA) shows a high interest in “sustainability” messaging, which is driven by consumer demand for ecolabels and sustainably production practices, while the Global South (China) shows a relatively higher interest in messaging around “safety” and “quality”. The preference for sustainable products comes from moral values and ethical considerations. The use of “safety” messaging can be traced back to concerns around food safety due to a lack of an established cold chain and, more broadly, standard operating procedures, already established by supermarkets and large retails in the Global North. The use of “quality” messaging is strongly associated with virtue signaling the natural characteristics and health benefits of seafood consumption in the Chinese market. Understanding the preferences of consumers across different socio-economic and cultural resolutions could improve business practices and better meet the expectations of the consumer, while improving production practices at the same time. Messaging strategies could be adjusted and improved to highlight the products' unique selling points and to find a match with the right customer.

CHAPTER 7: GENERAL DISCUSSION ON THE SUSTAINABLE INTENSIFICATION STRATEGIES FOR THE EUROPEAN AQUACULTURE INDUSTRY

7.1 Introduction

European aquaculture is lacking scale, and growth capacity is undermined by cheaper alternatives from capture fisheries and (aquaculture) imports (FAO, 2010; STECF, 2021; Asche, 2015). This emphasises the need to increase resource efficiency to improve the economic performance of the industry, while reducing the environmental footprint at the same time. Downstream in the value chain, the use of the whole fish needs to be made a more explicit part of sustainability thinking, strategically utilising co-products into food, feed and industrial applications to increase the economic output of the industry (Stevens *et al.*, 2018). In most cases, more economic value is accumulated towards the market-end of the value chain, indicating additional economic potential to increase processing by supplying more value-added and fresh seafood products (personal communication, Prof. Jimmy Young (2023)). Additionally, the upstream value chain is considered a sustainability hotspot, as most of the aquaculture production costs and environmental impacts are related to feed input (Bohnes *et al.*, 2018; Rana, Siriwardena and Hasan, 2009). More specifically, while marine ingredients, such as FM and FO have environmental concerns, this is also the case for their substitutes, such as plant derived meals and concentrates (Newton and Little, 2018; Blanchard *et al.*, 2017; Malcorps *et al.*, 2019a). While feed provisioning is an important component in the sustainable intensification process (Little *et al.*, 2018), it is crucial to find ingredients that use land, water and nutrients efficiently, while minimizing the negative impact on ecosystems and biodiversity (FAO, 2011; Foley, 2011). Such a basket of ingredients should include fish and agricultural by-products, as well as promising novel feed ingredients, meeting the nutritional demand of the farmed fish, while optimising economic and environmental performance.

Central to this chapter is the discussion around the sustainable intensification strategies for European aquaculture considering the literature on the European seafood market and the growth barriers that European aquaculture is facing (CH1-2). This is also discussed in relation to the stakeholder perceptions analysis (CH3). Both sustainable intensification strategies are further explored to identify their optimal use in the value chain. Downstream in the value chain, while exploring the findings of CH4, focus will be laid on the geographical discrepancies of processing and the benefits of a strategic processing and utilisation. This is discussed around envisioned geographical processing and utilisation clusters, where knowledge and technology can be exchanged and utilised to advance the resource efficiency performance and growth of European aquaculture species. This includes domestic utilisation of aquaculture processing by-products, as well as high-value exports to emerging markets, such as in China. As shown in CH6, food quality and safety are key food values messaged by Chinese seafood traders. This indicates opportunities for European seafood producers known for their high food standards, especially for Atlantic salmon, which is not produced in China (Asche *et al.*, 2022), and is already an accepted high-value species in the Chinese market (Stevens *et al.*, 2018). Additionally, upstream in the value chain, the stakeholder perceptions (CH3) and findings of CH4-5 are discussed in relation to a shift towards aquafeed 3.0, where the circular economy could play a crucial role in feed provision. While the scope of this thesis is limited to European aquaculture, the implementation of sustainable intensification strategies is likely to impact the sustainability performance and resilience of the broader European food system and is therefore briefly discussed.

7.2 Sustainable and resilient food production systems

Diversified systems are often more resilient and capable to withstand disruption, because they have more options available to mitigate negative impacts and overcome shocks, such as disease, weather events, inflation and social unrest (Cook *et al.*, 2015; Garnett and Godfray, 2012). For example, industrial farming supported by technologies might be more resilient to some environmental shocks, but maybe more sensitive to economic shocks related to its reliance on expensive inputs for production (Cook *et al.*, 2015; Garnett and Godfray, 2012). Adaptable and more resilient systems require continuous improvements, such as biological, social and institutional developments (Cook *et al.*, 2015). According to Pretty (2008), principles such as nutrient cycling, reducing the need for non-renewable inputs, as well as collaboration efforts, are principles that could have a significant impact on sustainability and resilience of the (agricultural) system. Understanding the contribution of aquatic animal production to the global food system requires a comprehensive understanding of wider food system literature (Halpern *et al.*, 2019). This is important because some forms of aquaculture show high levels of interaction and nutrient flows with fisheries and agriculture (Blanchard *et al.*, 2017; Pounds *et al.*, 2022). On the other hand, certain aquaculture activities show ecologically beneficial outcomes, such as species recovery, habitat restoration and coastal defence (Overton *et al.*, 2023). Aquaculture production systems are highly diverse and the impact on nutritional outcomes, livelihoods and the environment differs depending on trade, nutritional provision, consumption preferences (e.g., fillet vs whole fish) and the role of the circular economy (Pounds *et al.*, 2022). More specifically for aquaculture, as defined by Troell *et al.* (2014), improved resource efficiencies, increased diversification of farmed species, as well as improved feeding strategies are crucial components to enhance the resilience of the (European) food system. In CH3, I discussed the findings of the Norwegian and Polish key informants, who clearly showed a consensus on the "reduction and better use of by-products and waste". They also acknowledged importance of "collaboration between stakeholders" to advance sustainable intensification. The stakeholders from both Norway and Poland also demonstrated a clear consensus towards the importance of "government support in the form of

R&D or financial input”, while the Polish stakeholders emphasised the importance of “EU funds” to advance sustainable development.

While food systems show highly variable environmental impacts along the supply chain, certain nodes such as processing shows potential for substantial impact mitigation (Waite *et al.*, 2014; Poore and Nemecek, 2018). For example, wastages from processed seafood are approx. 8% lower compared to fresh unprocessed seafood (Poore and Nemecek, 2018; Cui, Zhang and al., 2018), emphasising the importance of processing, treatment and utilisation of by-product elsewhere to reduce wastages. This is in line with the findings discussed in CH4, which showed that increased processing of e.g., Atlantic salmon results in a significant proportion of available by-products for other applications, compared to less processed species such as common carp or species farmed in the Mediterranean. This suggests significant geographical variation in terms of available by-product volumes. In CH3, the Polish common carp stakeholders indicated that carp processing and year around appeal for carp could be improved by “changing consumer perceptions”, “diversify carp products by increased processing”, and through “marketing/advertising campaigns” and “subsidies or incentives”. This could be achievable, as it is demonstrated by the increasing levels of processing and export of common carp in the Czech Republic (FAO, 2023c). This is in line with the study of Martin (2009), who identified increased production capacity, nutritional understanding, marketing campaigns and disease control, as suitable strategies that transformed the British Turkey production from seasonal to a year around consumption activity. Similar strategies have also been acknowledged by the FAO (2023a; 2023f), as a way to enhance future growth of Mediterranean aquaculture through value-added product diversification and improved marketing organisation. However, consumer “conservatism” towards whole fish consumption is identified as a significant barrier (FAO, 2023f; FAO, 2023a). It is important to find ways to change consumer preferences towards processed seafood to unlock the economic and sustainability potential of increased processing and strategic utilisation in human food applications. While this strategy benefits the sustainability of downstream processing, it could indirectly improve the sustainability of (European) animal feed provisioning as well. This is crucial, because the EU is the largest user of proteins produced from vegetable origins, and reducing the dependency on feed protein imports was also considered an important strategy towards a sustainable transformation of the EU food system (FEFAC, 2023).

7.3 Maximise processing

Norway as a role model

In CH3 the Norwegian panel of experts identified “production limits imposed by the government” as a main barrier for industry growth, while “circular economy/recycling”, among “novel feed ingredients” and a focus on “quality rather than quantity”, were considered appropriate strategies to increase profitability. The by-product analysis in CH4 has clearly demonstrated interesting nutritional potential, as well as large volumes of mainly Atlantic salmon primary processing by-products available in Norway, while most secondary by-products accumulate in Poland. Most of the by-products in Norway are utilised in human food or animal feed (Richardsen *et al.*, 2017), but there is still potential to increase volumes and value addition within Norway (Olafsen *et al.*, 2014). This was in line with the findings in CH4, still indicating unrealised processing potential along the Norwegian Atlantic salmon value chain, such as in Poland where secondary processing takes place. This was also mentioned in the study of Asche *et al.* (2018), emphasizing that the Norwegian Atlantic salmon industry is advanced, but still considered semi-automated when compared to the often fully-automated food processing environments now used in the poultry industry. Investment in automation could reduce reliance on cheap labour for secondary processing (reduced economic opportunities in Poland) and increase the complete domestic processing of Atlantic salmon in Norway.

Outsourced processing

The findings of the by-product analysis in CH4 clearly showed that Poland (that barely farms any Atlantic salmon) had the second largest total volume of Atlantic salmon by-products and largest volumes of Atlantic salmon heads, frames, and trimmings each, available in the EEA. According to STECF (2021), this can be explained by the outsourcing of the secondary processing stage to other European countries, including Poland, which is incentivised by low labour costs. The by-product analysis in CH4 identified Denmark as the country with the third largest volumes of available Atlantic salmon by-products. Interestingly, while Danish labour costs are relatively high, new processing technologies and automation increased the economic performance of the processing industry. This also included the avoidance of unexpected outsourcing costs, such as poorly trained staff and communication issues leading to food safety, quality, and logistical issues (STECF, 2019). This model could be adopted by Norway to reduce reliance on outsourcing countries and increase domestic primary and secondary processing and value addition to retain more value out of their domestic production.

The by-product analysis in CH4 provided insight in the available by-product volumes on an EEA country resolution, but by-product utilisation efficiency and specific applications are still relatively unknown. This is in line with the study of Aas *et al.* (2022a), highlighting the lack of data on the utilisation of cut-offs of whole salmon exported to other countries (than Norway). This data is crucial in order to determine the resource efficiency of the industry, in particular in relation to the retention of valuable EPA+DHA in the fillet (32%) compared to the whole fish (49%) (Aas, Åsgård and Ytrestøyl, 2022a). EPA+DHA are in short supply and deficient in large parts of the world (Hamilton *et al.*, 2020), while the nutritional analysis in CH4 clearly indicated a significant amount of EPA+DHA and other beneficial nutrients embodied in most by-products, such as heads, frames, trimmings and skin from Atlantic salmon, European seabass, gilthead seabream and turbot frames.

A fish processing and utilisation cluster

Utilisation of by-products in countries like Poland and Norway could be further optimised to maximise the food, feed, and non-food value output. These countries could benefit by intensifying their processing and value-added industry and diversifying their product portfolio. According to Asche *et al.* (2018), less developed aquaculture value chains in Europe could adopt knowledge and technology to enhance further improvements. In CH4, the by-product analysis indicated nutritional potential of common carp by-products, but only small quantities are available due to a lack of processing. This can be explained by the tradition to purchased common carp alive or fresh, mainly during Christmas or Easter (EUMOFA, 2021a). Live sales of carp are reflected in the by-product analysis in CH4 by the large share of unrealised processing potential for viscera (Figure 4.4), which is for most other European species separated during the primary processing stage. In CH3, the Polish key informants also indicated “steady production volumes with declining financial margins”, which according to Raftowicz (2020) could be partly explained by the seasonal demand affects, which limits the ability to scale the common carp production. In CH3, the Polish key informants showed a consensus on carp processing as a suitable strategy to increase the profitability of the industry among other activities at the farm (tourism and efficient predator control), which was in line with the study of Lasner *et al.* (2020). In CH3, Polish key informants were also more specific on profitability through processing and identified fillet as the most profitable product form. However, as highlighted earlier, Polish key informants showed a clear consensus on the importance of changing consumer perceptions towards processed seafood, while promoting (media) a more diverse product portfolio. The Polish industry could learn from the Norwegians, and the outsourcing of Atlantic salmon processing in Poland might be the perfect opportunity to transfer technology and knowledge, as well as adopting distribution and marketing strategies to intensify processing and diversify its product portfolio. This could increase the economic performance of the common carp industry in Poland, as shown in the carp processing model case study in CH4, showing higher economic value output for a fully processed and utilised carp. The Polish carp industry could also learn from the commercialisation of the British Turkey production, which transformed from a seasonal activity to intensive mass production, driven by increased production capacity, nutritional understanding, marketing campaigns and disease control to increase appeal year around (Martin, 2009).

The key informants from the Norwegian and Polish value chain in CH3 considered increased processing and utilisation as an important sustainable intensification strategy to increase profitability. The suitability and potential impact of these strategies could vary depending on other factors. For example, increased processing in the EU could also be incentivized by financial benefits (e.g., tax cuts) for imported whole fish for processing and re-export purposes, which could benefit the resource efficiency and competitiveness of the processing sector. This is shown in the study of Asche *et al.* (2022) by the example of China, which processed and re-exported approx. 75% of seafood imported into the country. Processing companies often focus more on export than domestic markets, as a result of taxed free exportation to promote international trade of e.g., tilapia species (Moloko, Mathew and Yongming, 2013). Chinese labour costs are relatively low and manual processing gives higher yields compared to machine processing (Ng, 2007), while imports enabled companies to process year around and utilize their full capacity and enhancing their competitiveness, compared to processors that showed a dependency on seasonal processing (Birkenbach, Kaczan and Smith, 2017). In the case of Europe, this could be a suitable strategy for countries with low wages. Another suitable species candidate could be imported whitefish, such as farmed pangasius, which shows potential to substitute white fish imports from capture fisheries (Little *et al.*, 2012). The sanctions on the Russian whitefish industry (e.g., pollock and cod), might create opportunities for Vietnamese pangasius to fill the supply gap (IntraFish, 2022). According to the EU fish processors and traders association, a steady supply of imported whitefish to produce added value seafood in Europe is considered a key factor to expand and maintain employment and trade opportunities (Turenhout *et al.*, 2022).

Gilthead seabream and European seabass

The by-product analysis in CH4 showed a large unrealised processing potential for heads, frames and trimmings from European seabass, gilthead seabream and turbot. Indicating a lack of secondary processing for those species. The lack of sufficient fish processing in Southern Europe was explained by consumer preferences for whole (gutted) fish (EC, 2018a), and most of the gilthead seabream and European seabass production in the Mediterranean is still consumed within the farmed production countries (STECF, 2021).

In the last decades, an increased supply (also from imports from e.g., Turkey) in combination with a lack of market expansion resulted in a drop in the species price. The industry responded by consolidation leading to larger and more profitable companies (Llorente *et al.*, 2020; Rad, 2007; Rad and Köksal, 2000; STECF, 2014; Wagner and Young, 2009). Nevertheless, despite the consolidation of the industry and increased production efficiencies, secondary processing is still lacking, mainly due to consumer preferences (EC, 2018a). Additionally, the sector is affected by relatively high costs of production due to high European labour costs and administrative obligations, negatively affecting their capacity to compete with non-European producers (Arikan and Aral, 2019; Bjørndal, Guillen and Rad, 2019; Bozoglu and Ceyhan, 2009; Koçak and Tatlıdil, 2004; STECF, 2016; STECF, 2018). Nevertheless, the nutritional analysis of by-products in CH4 showed interesting nutritional characterisation of European seabass and gilthead seabream, especially regarding their valuable EPA+DHA content. This indicated significant untapped (economic) potential to diversify the product portfolio of European seabass and gilthead seabream through strategic utilisation of their by-products to maximise food, feed, and economic output. This opportunity has been acknowledged by Croatia, according to STECF (2021), which recently made significant investments in value added processing of these species to increase production efficiency and expand their product portfolio. However, this would require a consumer preference change from whole fish to processed products. This would allow the industry to accelerate production innovation, while increasing its resource efficiency and therefore enhancing its economic and environmental performance. Mechanical separation processes for example could better exploit European aquaculture species of interest, but oxidative processes during such treatment have to be limited and kept under control to maintain properties, such as quality, colour and anti-oxidant capacity (Secci *et al.*, 2016).

Turbot

The EU turbot industry saw a consolidation trend in the largest producing countries, such as Spain and the Netherlands, which enhanced the economic performance of the larger companies through economies of scale, technical innovation, and new markets, such as large retailers and supermarkets. In contrast, the French turbot sector consists of small companies with an associated low economic performance (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022). Nevertheless, most of the production is sold fresh and whole, while some is gutted (Fernández-González, Pérez-Pérez and Correia-da-Silva, 2022; SABI, 2021). The by-product analysis in CH4, clearly showed that turbot had the lowest fillet yield (30%) of all the European aquaculture species assessed, while a large unrealised processing potential for heads, frames and trimmings was observed. The relatively large proportion of the bodyweight is represented by by-products, and they show interesting nutritional characteristics, in particular for protein (heads and skin) and EPA+DHA (frames). In combination with increased scale, this could create processing and utilisation incentives, which could increase the economic performance of the industry. While this is beneficial for the whole industry, in could be an interesting opportunity for smaller sized turbot producers who are disadvantaged by the low financial performance.

7.4 Strategic utilisation to maximise economic output

The fish by-product hierarchy of Stevens *et al.* (2018), based on the Food Recovery Hierarchy from the USEPA (2020), is developed from a food security perspective and therefore prioritising the use of by-products in human food for domestic consumption and exports. Domestic consumption should be prioritised, but exports provide economic opportunities, as shown by the large volumes of exported by-products (10% of Norwegian Atlantic salmon heads and frames), used in e.g., Asian soups (Stevens *et al.*, 2018). China is importing an increasingly large proportion of its seafood supply (Fabinyi *et al.*, 2016). Urbanisation and rising income levels drive demand for high-value species in emerging markets, such as Atlantic salmon in China (FAO, 2018), where it is already an accepted high value species (Stevens *et al.*, 2018). In China, contrary to other species and the cultural norm, Atlantic salmon is not processed and re-exported, but only imported for domestic consumption, because there is no domestic production (Asche *et al.*, 2022). This indicates opportunities for European by-product utilisation and exports. However, it is important when exporting to other countries to take consumer preferences into account. Chinese consumers have a general preference for fresh seafood, which is often purchased “live”, compared to other product forms, such as frozen or canned seafood (Zhong, Crang and Zeng, 2019). It is estimated that a large proportion (~60–80%) of seafood in China is still purchased in live form in wet markets, without packaging, and not easy to label or trace. Consequently, the ability to promote certifications on these “unpacked” products is limited (Guan *et al.*, 2021; Peng *et al.*, 2020; Sun *et al.*, 2021), while Chinese seafood traders showed great interest in food safety and quality, according to the findings in CH6. Similar findings were observed in the study of Fabinyi (2016), highlighting that Chinese governance, traders, and consumers have a greater emphasis on food safety, traceability, quality, and freshness, rather than environmental sustainability. Therefore, packaging of fish by-products might be an accepted strategy, because it could address potential risk and consumer concerns associated with seafood consumption in Asia. More specifically, while most of the fish in China is sold fresh, live and unpacked (Zhong, Crang and Zeng, 2019), the main function of packaging is to prevent the spoilage of perishable seafood, while they also communicate values around safety, quality and convenience (Gokoglu, 2019). Additionally, packaging could also be produced from seafood waste, which is considered renewable, biodegradable, cost-effective and environmentally sustainable if collection and processing of seafood by-products is properly managed (de la Caba *et al.*, 2019). Altogether, this could unlock other benefits associated with packaging, such as brand recognition and awareness, potentially enhancing the sales volumes of unprocessed high value European fish by-products.

Enhanced processing into high value human applications, such as nutraceuticals, pharmaceuticals and hydrolysed proteins is prioritised by the hierarchy of Cooney *et al.* (2023), because it could potential unlock a larger economic value. This is contrary to the hierarchy of Stevens *et al.* (2018), which prioritises maximisation of the edible yield for domestic consumption and exports from a food security perspective. Nevertheless, in line with Stevens *et al.* (2018) and Cooney *et al.* (2023), when food grade requirements are not met, fish by-products could function as feed ingredients. Low environmental impact feed ingredients are particularly interesting for Europe's livestock and aquaculture sectors, reducing the need for (imported) marine ingredients from whole fish and their (plant) substitutes, as discussed in CH1-2.

7.5 Building communications and trust through value chains

Industry transparency is considered an appropriate strategy to improve the public perception towards aquaculture, according to the Norwegian panel of experts in CH3. There are concerns around greenwashing where companies deceive consumers into believing that a product is sustainable, without providing a way to verify this claim (Investopedia, 2022). Conventional certification has limited potential to address these issues, because (but not limited to) their top-down approach is challenging for local complexities of aquaculture production systems to be comprehensively accommodated, resulting potentially in the exclusion of local actors while favouring larger stakeholders (Mialhea *et al.*, 2018). A sustainable seafood industry and the strategic utilisation of by-products requires traceability and transparency along the supply chain to identify inefficient use of by-products, verify origin, as well as quality and treatments used. This is crucial to verify by-product status in relation to (EU) laws on category contamination and hygiene risks. Distributed ledger technology (DLT e.g., blockchain) shows potential to inform stakeholders on a shared network throughout value chains. Such a decentralised (public) record system allows for secure and transparent transactions, in which information entered (e.g., manual or through sensors) is nearly impossible to change or hack. The decentralised and immutable nature of a blockchain enables trust between stakeholders that facilitates increase supply chain efficiency and transparency, supporting circular economy principles and meeting consumer demands for sustainable products (Malcorps, Newton and Little, 2022). This technology shows promising characteristics to be applied in seafood value chains (FAO, 2020a), where it could also address mislabelling and fraud, which is a significant problem in the global seafood industry (Smejkal and Kakumanu, 2018; Fox *et al.*, 2018). This is also acknowledged by the EU, where combating seafood fraud is also part of the Farm to Fork strategy (EC, 2008; EC, 2020b).

7.6 A paradigm shift in feed ingredients

7.6.1 Aquafeed 3.0

Aquafeed formulations have evolved from being heavily dependent on marine ingredients (aquafeed 1.0) to a terrestrial plant and animal by-product diet (aquafeed 2.0) (Colombo and Turchini, 2021; Cottrell *et al.*, 2021), mostly driven by economic incentives and sustainability concerns in regards to a finite supply of ocean-derived ingredients (Naylor *et al.*, 2009; Pelletier *et al.*, 2018; Froehlich *et al.*, 2018). However, in CH3, the Norwegian panel of experts perceived that plant ingredients were insufficient to improve environmental sustainability, feed efficiency and fish welfare, while they showed a clear consensus on the high sufficiency of fishery processing by-products to improve the feed and environmental performance. This is also in line with the vision for aquafeed 3.0 by Colombo *et al.* (2021), using circular ingredients with sustainability benefits, while based on nutritious raw materials that are closer to the natural diet of farmed carnivorous aquatic species. The Norwegian key informants in CH3 highlighted the "use of fish by-products in other industries (e.g., feed)" and the "FIFO", as the 1st and 5th most important environmental sustainability indicators for their industry, respectively. According to Kok *et al.* (2020), including relatively "low economic value" fish by-products in aquafeed reduces the demand for wild-caught pelagic fish. Consequently, resulting in a lower FIFO, creating environmental and economic incentives to utilise by-products (Kok *et al.*, 2020).

Fish by-products in European FO and FM production

European FO and FM had relatively high by-product (capture fisheries and aquaculture) inclusions, representing on average 47% and 54% of the total European production between 2009 and 2013, respectively (Jackson and Newton, 2016). Nevertheless, most of the by-products in European FO and FM originated from wild capture fisheries (Jackson and Newton, 2016). More specifically, an estimated 1.17 million MT originated from capture fisheries, while aquaculture by-products only accounted for 331,000 MT (Jackson and Newton, 2016). This could be explained by the high European dependency on capture fisheries for its seafood supply (EUMOFA, 2022). This indicates opportunities to include large proportions of aquaculture processing by-products in FO and FM production.

Drivers and barriers of fish by-products as feed ingredient

There is a growing interest in adding value to aquaculture processing by-products due to consistent supply, higher uniformity and freshness compared to capture fisheries (Newton, Telfer and Little, 2014), while cost associated with storage and processing are expected to be lower for farmed production. In addition, most of the persistent organic pollutants (POPs), such as dioxins in farmed fish, originated from marine ingredients sourced from pelagic fisheries (Easton, Luszniak and Geest, 2002; Jacobs, Covaci and Schepens, 2002; Jacobs, Ferrario and Byrne, 2002). However, higher levels of POPs are more often observed in FO compared to FM (Easton, Luszniak and Geest, 2002; Jacobs, Covaci and Schepens, 2002; Jacobs, Ferrario and Byrne, 2002), but levels could vary depending on the fishing area, season, species and age (Bell and Waagbø, 2008; NORA, 2003; Glencross *et al.*, 2020; Lundebye *et al.*, 2004; Berntssen, Lundbye and Torstensen, 2005; Kelly *et al.*, 2008). The quality control of aquafeed ingredients has resulted in relatively lower contamination levels of farmed salmon in Europe compared to its wild counterpart (EFSA, 2012; Lundebye *et al.*, 2017; Glencross *et al.*, 2020).

Higher inclusions of aquaculture processing by-products in aquafeed is also subjected to legislative challenges, such as the documentation requirements for processors to meet necessary conditions and stands (Olsen, Toppe and Karunasagar, 2014). These administrative obligations limit countries like the Czech Republic, which is considered the largest European exporter of carp, to process their carp sufficiently before export, as only a few processing facilities comply with EU standards (FAO, 2023c). Such measures affect readiness to pursue greater processing and in the near term utilisation potential. Additionally, despite lifting the ban on the use of processed animal proteins in the EU, legislation for non-ruminants (which also includes fish), still prohibits intraspecies feeding in regard to protein meals (EC, 2021). This legislation is problematic for European aquaculture, because in the case of salmon, it is applicable to salmonids, which also includes rainbow trout. These species combined make up almost 67% of the EEA aquaculture production by volume in 2021 (FAO, 2023b). Both species showed a high dependency on a combined FM volume of approx. 185 and 70 thousand MT in 2020, sourced from forage fish and cut-offs, respectively (Aas, Åsgård and Ytrestøyl, 2022a; Aas, Åsgård and Ytrestøyl, 2022b). Consequently, creating a dependency on (foreign) capture fishery fleets to supply raw materials to produce FM for the Atlantic salmon and the rainbow trout industry.

Strategic feed application

In CH3, the Norwegian panel of experts selected the "use of fish by-products in other industries (e.g., feed)" as one of the most important environmental sustainability indicators. Atlantic salmon by-products in feed could also be directed towards other European aquaculture species, such as the carnivorous European seabass and turbot. However, the European market for these species is relatively small and therefore more popular species could be explored, such as is tuna (EUMOFA, 2022), with an increasing global demand (Benetti, Partridge and Stieglitz, 2016). Nevertheless, the sector is facing different challenges in relation to its dependency on capture fisheries for its supply of wild caught tuna juveniles, and feed ingredients. Bluefin tuna consumes large volumes of small pelagic fish, such as sardines and mackerel, and sustainable intensification would require feed innovation to improve the environmental and economic performance (Benetti, Partridge and Stieglitz, 2016). In CH4, the by-product analysis has showed that large quantities of by-products which are unattractive for use in food directly, such as viscera, as well as other by-products, such as head, frames and trimmings with high lipid and EPA+DHA content, could be directed to animal feed. A steady supply could be considered to support the farmed European tuna production. Alternatively, fish by-products could be upcycled in (European) livestock feeds, reducing the need for virgin resources that compete directly with agricultural food production (Sandström *et al.*, 2022). More specifically, but not limited to, Poland is the largest EU poultry meat producer (USDA, 2020), but there are concerns regarding the rising feed prices as a result of a growing demand for grain and the Ukrainian crisis (PoultryWorld, 2022). Denmark showed a high dependency on plant proteins for their large intensive livestock sector and leading pork production in the EU, according to ITA (2022), and fish by-products in the form of FM in the diet is beneficial to health and welfare, especially to the diets of pig and poultry (IFFO, 2017). Improved resource efficiencies, increased diversification of farmed species, as well as improved feeding strategies are crucial components to enhance the resilience of the (European) food system, according to Troell *et al.* (2014).

7.6.2 Novel feed ingredients

Optimising productivity is a key concept of sustainable intensification for agricultural systems, so that arable land does not have to be expanded with potential biodiversity and ecosystem loss (Cook *et al.*, 2015). In CH3, the Norwegian panel of experts showed a clear consensus on the limited potential of currently available plant ingredients to support sustainable intensification, fish welfare and nutritional outcomes. This is in line with the study of Colombo *et al.* (2021) highlighting that terrestrial crops in aquafeed compete directly with the resources required to produce human food (Colombo and Turchini, 2021), emphasizing the need for aquafeed ingredients that do not deplete natural resources (Colombo and Turchini, 2021). In CH3, the Polish panel of experts did not show a concern in relation to feed ingredients due to the low levels of feed application in the carp industry. However, they do consider land as one of the most important environmental sustainability indicators, which is significantly affected by using plant ingredients in aquafeed. While fish by-products show promising characteristics to reduce the environmental impact through improved resource efficiency, their use is prioritised in human food rather than feed, and sometimes restricted by legislation and documentation (Malcorps *et al.*, 2021c; Stevens *et al.*, 2018). The use of plant ingredients that compete with agricultural resources could be further reduced by the inclusion of novel (by-product) feed ingredients, such as microalgae and guar meal. In CH5, I discussed the findings of the production of these ingredients with limited use of agricultural resources, showing potential to be cultivated in the arid regions of Europe.

The LCA in CH5 showed a variable environmental performance between and within ingredients. It is important to take the source of energy into account, as microalgae meal produced with wind energy at the farm resulted in a relatively low GWP compared to microalgae meal produced with energy derived from the national grid of country (confidential). Additionally, microalgae were produced on non-productive arid land, therefore the impact on food production and related resource competition and GWP LUC is limited. The results in CH5 showed the importance of taking the production location and source of the energy (renewable vs non-renewable) into account, as this influences the environmental performance significantly. This is in line with the findings in the study of Maiolo *et al.* (2020b), concluding that the environmental impact of microalgae produced in energy intensive photobioreactors was mostly associated with the production location, in this case the energy mix of France and Italy (mostly fossil and nuclear). However, while the findings in CH5 are promising for microalgae and guar meal to reduce the environmental impact, their inclusion in the assessed feed formulations is relatively low. The rest of the feed formulation is made up of other ingredients, such as soybean derived ingredients (soybean protein concentrate and meal), wheat gluten and rapeseed oil, with relatively high values for most environmental impact categories. Consequently, sometimes neutralising the positive impact of microalgae and guar meal on the environmental performance of the feed formulation. It is therefore important to balance these ingredients well and only include the minimum amount necessary to meet nutritional requirements of the farmed fish to optimise resource trade-offs as best as possible.

It is crucial to find the right basket of ingredients, which are available, affordable, have a low environmental footprint and most importantly, meet the nutritional requirements of the farmed fish. Both microalgae, as well as guar meal, can be produced in the arid regions of Europe, such as the Mediterranean. While guar meal is a plant ingredient, it is also considered a by-product from the production of guar gum from guar seeds. The demand for guar gum has increased and most of the production is used by the oil and shale gas industry (Dezember, 2011; Sood and Paliwal, 2012; Kuravadi *et al.*, 2013; Mudgil, Barak and Khatkar, 2014). Ingredients produced through the circular bioeconomy, such as by-products from agricultural and fish processing, show potential to improve the environmental sustainability of diets (Colombo *et al.*, 2022; Colombo and Turchini, 2021). In this case sustainability is served through increased resource efficiency between the agriculture and aquaculture sector. Additionally, when environmental sustainability is assessed using LCA and economic allocation is applied, more impact will be assigned towards high value products, rather than relatively low value by-products. Lower economic value results in a relatively lower environmental footprint and therefore sustainability incentives to use low value by-products, according to the study of Regueiro *et al.* (2021).

7.7 Conclusion

Strategic by-product utilisation and novel feed ingredients are considered suitable sustainable intensification strategies for high value European farmed species. The less developed and resource inefficient supply chains, such as the Mediterranean farmed species could adopt knowledge, strategies and (processing) technology from the Norwegian Atlantic salmon industry. Common carp might be better fitted in a landscape food production system but could adopt some forms of processing to increase resource efficiency and economic performance. Additionally, Europe is highly dependent on imported animal feed ingredients, and opportunities to produce these ingredients domestically should be promoted. From a sustainability perspective, the use of low impact by-products from fisheries and agriculture in aquafeed should be further enhanced, as this enables increased resource efficiencies between aquaculture, agriculture, and fisheries. This could reduce the environmental footprint of aquaculture significantly, as most of the impact is associated with the use of aquafeed. While increased resource efficiency through strategic processing and utilisation improves the sustainability, it also benefits the economic performance and competitiveness of the industry. This is crucial, because according to a study by Zander and Feucht (2017), only a fraction of the consumers in Europe are willing to pay a significant higher price for sustainably produced fish. An European seafood consumption survey concluded that overall fish consumption in Europe is mostly influenced by price incentives (EC, 2018a). This highlights the importance to increase resource efficiency of European aquaculture production, supplying affordable, healthy, and nutritious seafood, while reducing dependency on finite capture fisheries and aquaculture imports.

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APPENDIX 1: SURVEYS

A1.1 KI - Norwegian Atlantic salmon

Introduction and verbal consent

My name is …………… and I am working for ………..

We have a research project "GAIN – Green Aquaculture INtensification in Europe" to support the ecological intensification of aquaculture in EU and the EEA. The objectives are to increase production and competitiveness of the industry while ensuring sustainability and compliance with EU regulations on food safety and environment.

Part of this project is to assess the consumers and stakeholders' acceptance of sustainable intensification measures for which we are conducting a survey for the key players along the value chain.

Would you be happy to participate in this survey and discuss your opinions/vision and your business plan regarding aquaculture intensification, it will take approx. 30 minutes? Yes/No.

Company/business and interview details

What is the main activity of this company, which sector this company can be classified (farming, processing, feed ……)?

What is your position/responsibility in this company?

How many years are you working in aquaculture?

How many years are you working for this company?

Value chain information

Total industry production (MT - feed, grow out, smolts etc.).

Type of products or activities (Producer, R&D, education etc. depending on stakeholder).

Comparison to other companies.

Number of companies in Norway.

Company production as % of total.

Main markets of total industry (domestic, international).

Transportation methods (% air/sea/land of total industry).

What are the main trends in the industry (growth, markets, practices, innovation, structural, managerial, consolidation, integration, new players, diversification, value addition)?

What are the main changes in your part of the industry?

What are the main changes in your company?

1.1 Can you rate the power and interest of the following stakeholders in terms of their position to make industry changes/innovate and how it could affect them? Score 1 (barely any influence) to 10 (highly influential).

Stakeholder	**Power**	**Interest**
Brood stock/egg producers		
Hatcheries (RAS)		
Smolt production (RAS)		
Smolt production (flow-through)		
Grow-out farms		
Independent slaughterhouse and primary processors		
Independent secondary processors		
Value addition processors/smokeries etc.		
Integrated companies		
By-product processors		
Cleaner fish producers		
Exporters/trading companies		
Retail		
Well-boat/transport		
Vet/health management companies		
Feed companies		
Ingredient producers (FO, hydrolysates/meals etc.)		
End users (pet food)		
Education groups		
Research innovation companies		
Trainers		
Equipment producers		
Government authorities		
Certifiers		
NGOs		
Consumer groups/associations		
Other support industries/suppliers (ice, chemicals, consumable products etc.)		

1.2 Do you participate in the following?

	No.	Length relation	Description
Association membership			
Workshop attendance			
R & D with academia/NGO			
R & D with commercial			
Government programme			
Other …..			

1.3 What stakeholders do you have most interaction with?

Name	Type (NGO, feed mill,..)	Relationship (customer,…)	Number meetings/year	Years of relationship

Knowledge, attitudes and perceptions regarding aquaculture intensification and sustainability.

By intensification, we mean producing more with fewer resources at all stages along the VC.

How do you see intensification in aquaculture (positives/negatives/impacts)?

Does your company have a vision/plan for sustainable intensification?

What are the current topics / processes on sustainability on which you are currently working?

1.4 What factors do you foresee that could positively or negatively affect your business performance over the next 5 years? Score 1 (negatively) to 5 (positively) or rank.

	Sustainability Factor	Overall Rank/Score	Response
Negative			
Positive			
Uncertain			

Within GAIN project we are proposing the following sustainable intensification measures, for each of these measures we would like to know your opinion and acceptance and if your company already applying or willing to adopt in the future. Please remember the following QS may not be applicable to all the measures bellow.

For each measure, please ask the following QS:

Have you heard about this measure?

Do you have any example of it being applied?

1.5 Production and environment.

Measure	Microalgae	Macroalgae	Hydrolysed fish proteins	Single cell proteins	Insect protein
Knowledge					
Company interest					
Industry interest					
Comment					

1.6 Enhancement of secondary outputs.

Measure	Sludge for fertiliser	Sludge for biogas	Mortalities for biogas	Processing by-products for feed	By-products for cosmetics/nutraceuticals
Knowledge					
Company interest					
Industry interest					
Comment					

1.7 Enhancement of secondary outputs.

Measure	Shells for biofilters	Shells for packaging	Shells for cement/filler	Use of big data management support	Use of big data for welfare
Knowledge					
Company interest					
Industry interest					
Comment					

Do you think there is enough information available for the awareness of sustainable aquaculture intensifications?

A1.2 KI - Polish common carp (distributed in English and Polish)

Introduction and verbal consent

My name is ……………(Code…..) and I am working for ……….

We have a research project "GAIN – Green Aquaculture INtensification in Europe" to support the ecological intensification of aquaculture in EU and the EEA. The objectives are to increase production and competitiveness of the industry while ensuring sustainability and compliance with EU regulations on food safety and environment.

Part of this project is to assess the consumers and stakeholders' acceptance of sustainable intensification measures for which we are conducting a survey for the key players along the value chain.

Would you be happy to participate in this survey and discuss your opinions/vision and your business plan regarding aquaculture intensification, it will take approx. 30 minutes? Yes/No.

Company/business and interview details

What is the main activity of this company, which sector this company can be classified (farming, processing, feed ……)?

What is your position/responsibility in this company?

How many years are you working in aquaculture?

How many years are you working for this company?

Value chain information

Who is producing?

How much are they producing?

Where are they producing?

Where is the value added?

Where are the products going?

Total industry production (MT - feed, grow out, etc.).

Type of products or activities (Producer, R&D, education etc. depending on stakeholder).

Comparison to other companies.

Number of companies in Poland.

Company production as % of total.

Main markets of total industry (domestic, international).

Transportation methods (% air/sea/land of total industry).

What are the main trends in the industry (growth, markets, practices, innovation, structural, managerial, consolidation, integration, new players, diversification, value addition)?

What are the main changes in your part of the industry?

What are the main changes in your company?

1.1 Can you rate the power and interest of the following stakeholders in terms of their position to make industry changes/innovate and how it could affect them? Score 1 (barely any influence) to 10 (highly influential).

Stakeholder	Power	Interest
Farms		
Feed companies		
Slaughterhouse and primary processing		
Value addition processing		
Import and trading company		
Retail company		
Transport		
Vet/Health management company		
Education		
Recreational (guide) tour		
Research and innovation company (R&D)		
Trainer institution		
Equipment producer, maintenance, and recycling		
Government and representative authorities		
Certification body/organization		
NGO		
Carp associations		
Consumer group		

1.2 Do you participate in the following?

	No.	Length relation	Description
Association membership			
Workshop attendance			
R & D with academia/NGO			
R & D with commercial			
Government programme			
Other …..			

1.3 What stakeholders do you have most interaction with?

Name	Type (NGO, feed mill,..)	Relationship (customer,…)	Number meetings/year	Years of relationship

Knowledge, attitudes and perceptions regarding aquaculture intensification and sustainability.

By intensification, we mean producing more with fewer resources at all stages along the VC.

How do you see sustainable intensification in aquaculture (positives/negatives/impacts)?

Does your company have a vision/plan for sustainable intensification?

What are the current topics / processes on sustainability on which you are currently working?

1.4 What factors do you foresee that could positively or negatively affect your business performance over the next 5 years? Score 1 (negatively) to 5 (positively) or rank.

	Sustainability Factor	Overall Rank/Score	Response
Negative			
Positive			
Uncertain			

Within GAIN project we are proposing the following sustainable intensification measures, for each of these measures we would like to know your opinion and acceptance and if your company already applying or willing to adopt in the future. Please remember the following QS may not be applicable to all the measures bellow.

For each measure please ask the following QS:

Have you heard about this measure/do you have any example of it being applied?
Score: (yes = 2; maybe/uncertain = 1; no = 0).

1.5 Production and environment.

Measure	Microalgae	Macroalgae	Hydrolysed fish proteins	Single cell proteins	Insect protein
Knowledge					
Company interest					
Industry interest					
Comment					

1.6 Enhancement of secondary outputs.

Measure	Sludge for fertiliser	Sludge for biogas	Mortalities for biogas	Processing by-products for feed	By-products for cosmetics/nutraceuticals
Knowledge					
Company interest					
Industry interest					
Comment					

1.7 Enhancement of secondary outputs.

Measure	Shells for biofilters	Shells for packaging	Shells for cement/filler	Use of big data management support	Use of big data for welfare
Knowledge					
Company interest					
Industry interest					
Comment					

Do you think there is enough information available for the awareness of sustainable aquaculture intensifications?

A1.3 Delphi survey round I - Norwegian Atlantic salmon

<u>MULTIPLE ANSWERS POSSIBLE.</u>

What is the general trend in the aquaculture industry in Norway?

- Increasing production volume.
- Steady production volume.
- Declining production volume.
- Increasing financial margins.
- Steady financial margins.
- Declining financial margins.
- Increasing “responsible” production.
- Steady “responsible” production.
- Declining “responsible” production.

Key aspects of environmental sustainability of the Norwegian salmon industry are…?

- Use of sustainable feeds.
- Supporting and invigorating isolated coastal communities.
- Technically efficient production.
- High fish welfare.
- Good site selection.
- Moving to offshore for grow-out.
- Greater use of RAS technology.
- Integrated Health management strategy.
- Minimizing escapes.

<u>LIKERT SCALE (CHOOSE 1).</u>

Within Norway, the Norwegian aquaculture industry is perceived as sustainable.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

In Europe, the Norwegian aquaculture is perceived sustainable by the general public.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

EU legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

EU legislation is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

National legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

National legislation is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

Provincial (regioner) legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

Provincial (regioner) is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

SCORE 1 to 8 (1 not important, 8 highly important).

What is needed to support the sustainable growth in aquaculture.

- Collaboration between stakeholders.
- Government financial support (credit, insurance, upgrade grants etc.).
- Government training program.
- Government support in the form of market access.
- Government support in the form of R&D.
- Re-investment incentives in salmon business.
- Cross sectoral investments (e.g., fisheries invest in salmon).
- Foreign investment.

What are appropriate strategies to increase the profitability of the salmon industry?

- More regulations on production volume output.
- More regulations on feed use.
- More regulations on salmon lice treatments.
- Increased production.
- Focus on quality rather than quantity.
- More certification.
- Improve traceability.
- Novel feed ingredients.
- Circular economy/recycling.
- Linking farms to the national energy grid.
- Transition towards renewable energy production on site.

What could be done to improve public perception towards the aquaculture industry and its products?

- Certifying more production sites.
- Government advertising campaigns.
- Increasing transparency.
- Promotion in the media.
- Move towards precision aquaculture approaches (automation and use of sensors).
- Circular economy/recycling.
- Substitution of standard/traditional feed ingredients with novel feed ingredient.

Which of these technologies show most potential to combat sea lice?

- New chemical treatments.
- Better use of existing chemicals.
- Data sharing between farms to predict/prevent sea lice outbreak.
- Cleaner fish (e.g., lumpfish, wrasse).
- RAS to produce super smolts e.g., up to +600 grams.
- RAS for the entire cycle.
- Other closed or semi-closed containment systems.
- More offshore sites (i.e., higher exposure).
- Other physical sea lice exclusion technology.
- A combination of several technologies.

How much potential do the novel feed ingredients for salmon diets below show for improving the environmental sustainability?

- Plant ingredients.
- Marine ingredients from fishery processing by-products.
- Insect protein.
- Microalgae.
- Seaweed.
- Bacterial cell proteins.

How much potential do the novel feed ingredients for salmon diets below show for improving the feed efficiency?

- Plant ingredients.
- Marine ingredients from fishery processing by-products.
- Insect proteins.
- Microalgae.
- Seaweed.
- Bacterial cell proteins.

How much potential do the novel feed ingredients for salmon diets below show for improving the fish welfare?

- Plant ingredients.
- Marine ingredients from fishery processing by-products.
- Insect proteins.
- Microalgae.
- Seaweed.
- Bacterial cell proteins.

Which novel feed ingredients show most potential to improve the public consumer perception of farmed fish?

- Plant ingredients.
- Marine ingredients from fishery processing by-products.
- Insect proteins.
- Microalgae.
- Seaweed.
- Bacterial cell proteins.

We have conducted a sustainability assessment of the industry and have collected data for the following indicators. We wish to weight the sustainability indicators based on the importance for the industry. We want to know what the industry thinks! Please SCORE each indicator from 1-8 from least important to highly important as a sustainability indicator.

Economic:

- Number of fish rejected at processing plant.
- Feed efficiency.
- Farm operating costs.
- Renewable energy production within farm.
- Domestic/export market destination.
- Mortality at farm.
- Diversity of products (e.g., fillets, smoked, value add).
- Market destinations (e.g., restaurants, retail).

Environment:

- Renewable energy use on the farm.
- Antibiotic use.
- Chemical use.
- Regular water quality checks.
- Oxygen demand (COD/BOD).
- Suspended solids in the water column.
- Benthic impact.
- Recycling by-products in other industries (e.g., feed).
- Greenhouse gases/carbon footprint.
- Freshwater consumption.
- Acidification.
- Nutrient release in the environment.
- Land footprint.
- Energy consumption.
- Feed efficiency.
- Fish-in-fish-out.
- Presence of impact reduction mitigation (e.g., drain traps).

Social:

- Labour and wage structure.
- Number of employees per unit output.
- Output value per employee.
- Employee risk to hazardous/chemicals.
- Employee safety and risk reduction.
- Certification.

Welfare:

- Amount of emergency harvests.
- Cleaning of the nets (frequency).
- Number (%) of farm mortalities in cycle.
- Observation of body damage.
- Humane slaughter of fish.
- Anti-predator measures (e.g., seal scarers).
- Average stocking density.
- Fish welfare training for employees.
- Health management plan.

A1.4 Delphi survey round I - Polish common carp

<u>MULTIPLE ANSWERS POSSIBLE.</u>

What is the general trend in the carp aquaculture industry in Poland?

- Increasing production volume.
- Steady production volume.
- Declining production volume.
- Increasing financial margins.
- Steady financial margins.
- Declining financial margins.
- Increasing “responsible” production.
- Steady “responsible” production.
- Declining “responsible” production.

What is needed to increase the processing of carp?

- Change in consumer perception.
- Diversifying market.
- Legislation on live sales.
- Influence from NGOs or other pressure groups.
- Subsidies or incentives.

What aspects of the carp farming industry should be promoted?

- Low impact.
- Natural production.
- Organic.
- Traditional.
- Local.
- Tasty.
- Healthy.

LIKERT SCALE (CHOOSE 1).

Within Poland, the Polish carp aquaculture industry is perceived as sustainable.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

In Europe, the Polish carp aquaculture is perceived sustainable by the general public.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

EU legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

EU legislation is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

National legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

National legislation is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

Provincial (voivodeship) legislation is supporting the growth (production volume output) of the aquaculture industry.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

Provincial (voivodeship) legislation is supporting the aquaculture industry to become more environmentally friendly.

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

Carp processing could increase profitability of the industry?

- Strongly agree.
- Agree.
- Neither agree or disagree.
- Disagree.
- Strongly disagree.
- Not sure.

SCORE 1 to 8 (1 not important, 8 highly important).

What actions could be done to improve perception towards the aquaculture industry?

- Certifying more production sites.
- Improve water quality.
- Circular economy and recycling.
- Ban live sales.
- Lower environmental impact.
- More humane predator control.

In terms of marketing and promotion, what could be done to improve perception towards the aquaculture industry and its products?

- Media promotion.
- Government advertising campaigns.
- Celebrity endorsements.
- Increasing transparency.

What is needed to support the sustainable growth in carp aquaculture?

- Collaboration between stakeholders.
- EU funds.
- Government financial support (credit, insurance, upgrade grants etc.).
- Government training program.
- Government support in the form of market access.
- Government support in the form of R&D.
- Cross sectoral investments (e.g., fisheries invest in carp aquaculture).
- Foreign investments.

What are appropriate strategies to increase the profitability of the carp industry?

- Change regulations on production volume output.
- Intensification (increase yield per hectare).
- Focus on quality rather than quantity.
- More certification.
- More (EU) funding to protect natural areas (e.g., Natura 2000).
- Improve traceability/better record keeping.
- Better feed technology.
- Circular economy/recycling.
- Increase processing.
- Diversification of activities at the farm (e.g., tourism, other aquaculture species).
- Efficient predator control.

How can the year around appeal for carp being improved?

- Diversify carp products (increase processing).
- Consumer perception change.
- Organizing promotion events.
- Marketing/advertising campaigns.
- Government financial incentives.
- EU funds to promote carp consumption through the year.
- Other investments to promote carp consumption through the year.

What are suitable mitigation strategies against the effects of climate change for Polish carp aquaculture?

- Use water resources more efficiently.
- Engineering solutions (e.g., water channels).
- Improved water quality management (e.g., checking oxygen, ammonia levels).
- Improved health management (e.g., veterinary checks, vaccination etc.).
- Better record keeping.
- Breeding programs for resilience.

What are appropriate strategies to improve the image of carp farming.

- Ban sale of live car.
- Humane slaughter.
- More processing.
- Increase transparency of the industry.
- More education.
- Increase awareness.

What is the most profitable carp product? (Score: 1 low profitability, 8 high profitability)?

- Traditional (live).
- Head on-gutted.
- Carcass.
- Slice (steak).
- Sheet.
- Fillets.

We have conducted a sustainability assessment of the industry and have collected data for the following indicators. We wish to weight the sustainability indicators based on the importance for the industry. We want to know what the industry thinks! Please SCORE each indicator from 1-8 from least important to highly important as a sustainability indicator.

Economic:

- Farm operating costs.
- Renewable energy production within farm.
- Domestic markets vs export markets.
- Diversity of products/market destinations.

Environment:

- Renewable energy use.
- Chemical use.
- Regular water quality checks.
- Greenhouse gases/carbon footprint.
- Freshwater consumption.
- Acidification.
- Nutrient release in the environment.
- Land footprint.
- Energy consumption.
- Impact reduction mitigation (e.g., bird nets).
- Cleaning of ponds and chemicals used.

Social:

- Labour structure (proportion of e.g., workers, managers).
- Jobs created per unit output.
- Employee risk to hazardous/chemicals.
- Employee safety and risk reduction.
- Certification.

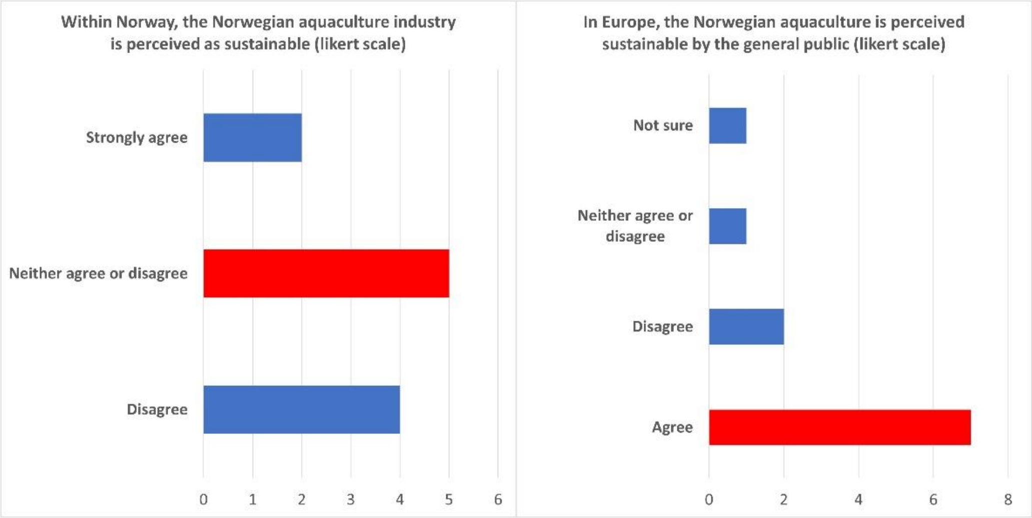
Welfare:

- Amount of emergency harvests.
- Number of mortalities on farm.
- Observation of body damage.
- Humane slaughter of fish.
- Predation measures (e.g., bird nets).
- Average stocking density.

A1.5 Delphi survey round II - Norwegian Atlantic salmon

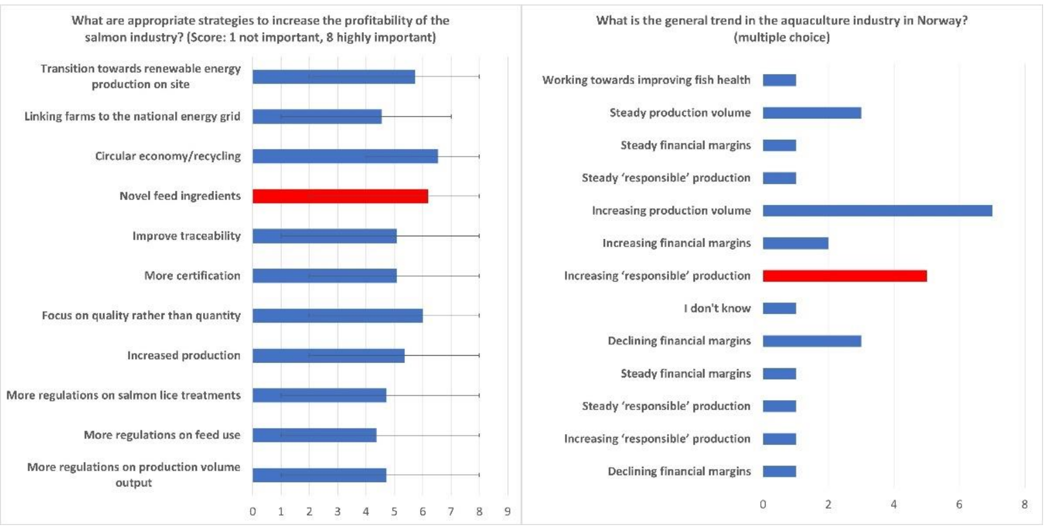
Score: 1 not important, 8 highly important.

In round 1 (see graphs) we asked about the environmental impact of the Norwegian aquaculture industry. Respondents indicated (red bar in graphs) that they perceived that EU consumers regarded Norwegian aquaculture to be more sustainable than Norwegian consumers did. What can explain these different perceptions?



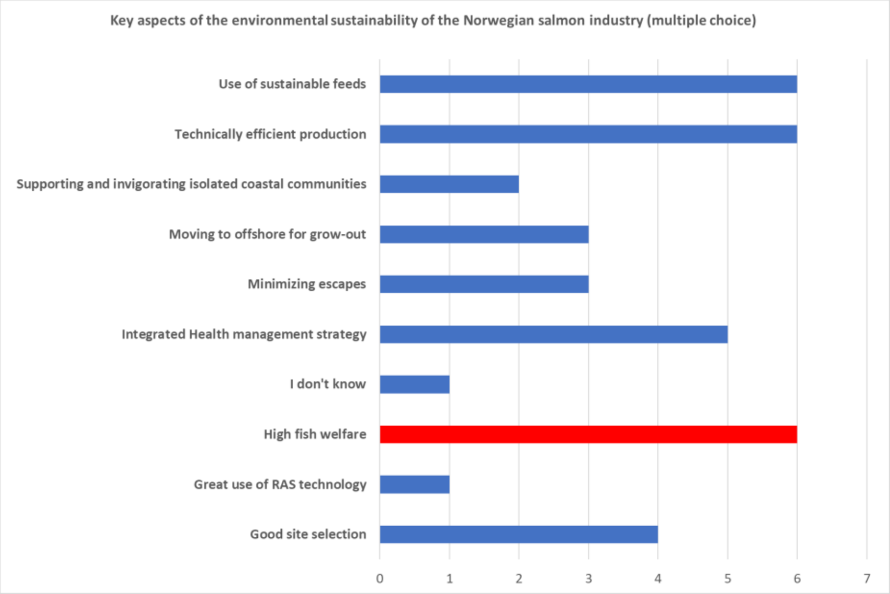
- *Norwegians are more aware than EU consumers on seafood's sustainability challenges.*
- *EU consumers consider Norwegian salmon to be of uniformly high standard.*
- *EU consumers think that Norway has a pristine environment.*
- *Perceptions on the definition of sustainability differs.*
- *EU consumers consider Norwegian salmon sustainable compared to their own local products.*

In round one we asked about general trends in the aquaculture industry in Norway. Respondents highlighted a trend towards "responsible" production (graphs below, red bar). Respondents also indicated that novel feed ingredients were considered a key strategy to increase profitability and sustainability. What are the main challenges of novel feed ingredients?



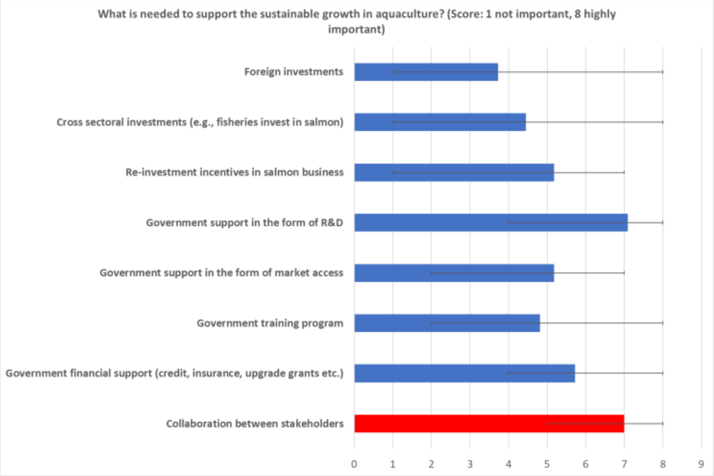
- *Availability.*
- *Quality.*
- *Consistency of nutritional content.*
- *Legislation.*
- *Price.*

In round one we asked about environmental sustainability (graph below, red bar). In addition to sustainable feeds and technically efficient production, stakeholders highlighted the importance of high fish welfare (red bar). What are key strategies to support fish welfare?



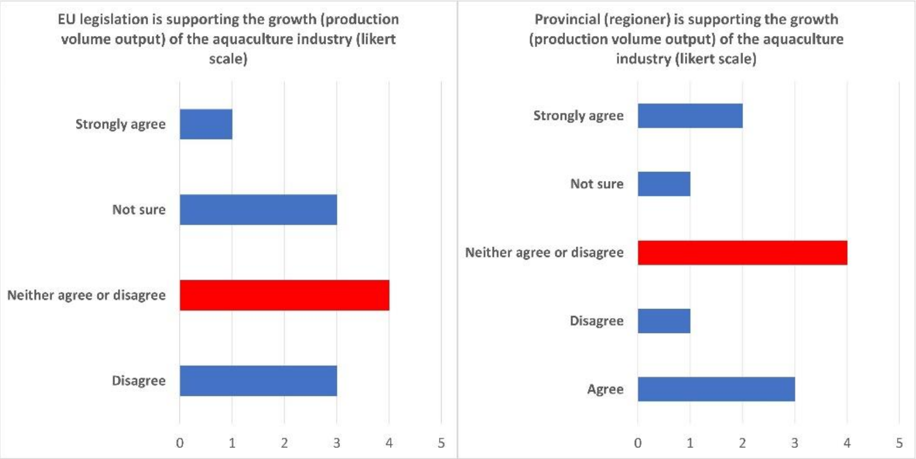
- *Regulator veterinary checks.*
- *Implement training in fish welfare.*
- *Monitor fish condition.*
- *Monitor water quality (temperature, pH etc.).*
- *Predator control.*
- *Feed quality assurance.*

In round one we asked about the needs to support sustainable growth. Respondents indicated that collaboration between stakeholders is very important to support sustainable growth (graph below, red bar). What type of collaboration is most important?



- *Implementing an area warning system for sea lice.*
- *R&D on sustainable feeds.*
- *Sharing farm performance data.*
- *Regular producer meetings to refine collective strategies.*

In round one we asked if current EU and provincial (regioner) legislation is supporting growth (production volume output) of the Norwegian aquaculture industry. Respondents had mixed views about legislation in terms of supporting the growth of the industry (graphs below, red bar). Where should legislation focus to achieve sustainable growth?

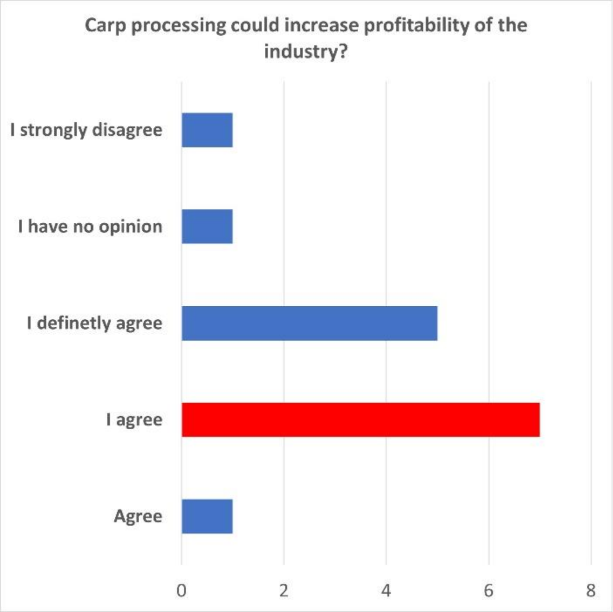


- *Legislate on environmental footprint, e.g., carbon.*
- *Financial instruments (e.g., subsidies, incentives, tax benefits) for innovations.*
- *Improving the planning for new site selection.*
- *Replace government regulation with private standards (e.g., ASC or GlobalG.A.P.).*
- *Reduce regulation on salmon lice treatments.*
- *Reduce regulation on feed use.*
- *Site or context specific regulation on maximum standing biomass.*

A1.6 Delphi survey round II - Polish common carp (distributed in English and Polish)

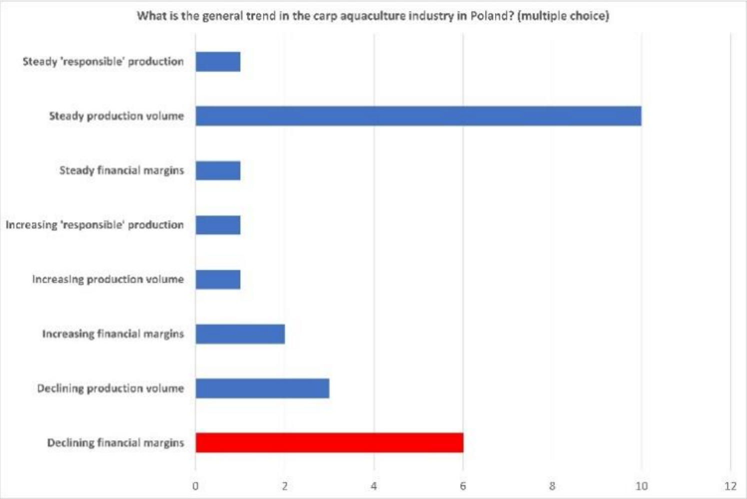
Score: 1 not important, 8 highly important

In round one we asked if carp processing could increase the profitability of the Polish aquaculture industry. Respondents indicate that carp processing could increase the profitability of the industry (red bar). What is the best strategy to change consumer perceptions towards processed carp?



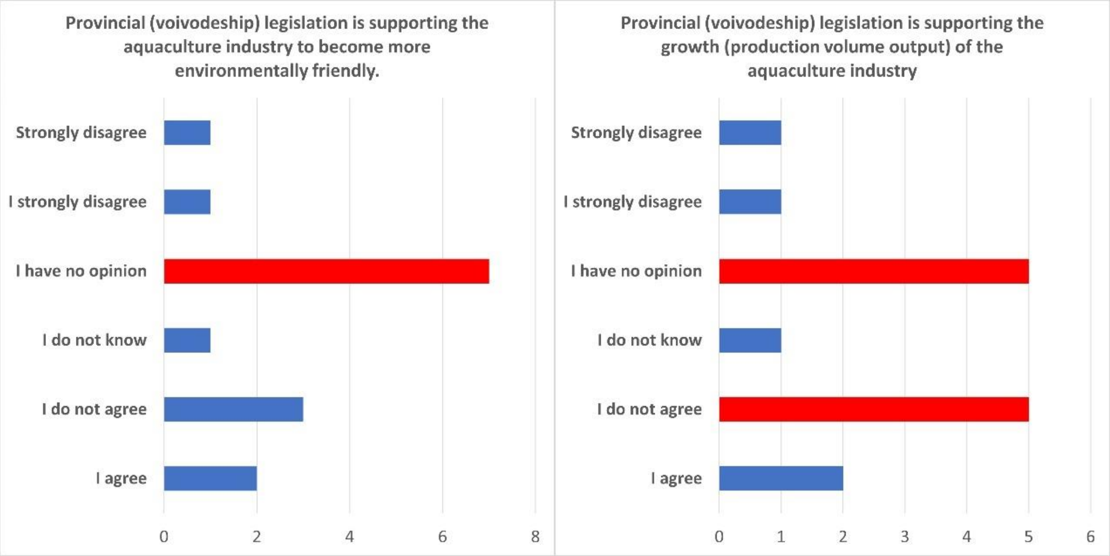
- *Advertisements: "live sales are cruel".*
- *Advertisement to stimulate people to eat processed carp all year.*
- *Better advertising campaign for differentiated carp products.*
- *Create economic incentives (tax cuts or subsidies on processed carp products).*
- *Industry promotion of natural production characteristics of processed carp products.*

In round one we asked about the general trends in the carp aquaculture industry in Poland. In addition to a steady production volume, respondents identified a perception of reducing profit margins (graph below). What has caused the declining financial margins?



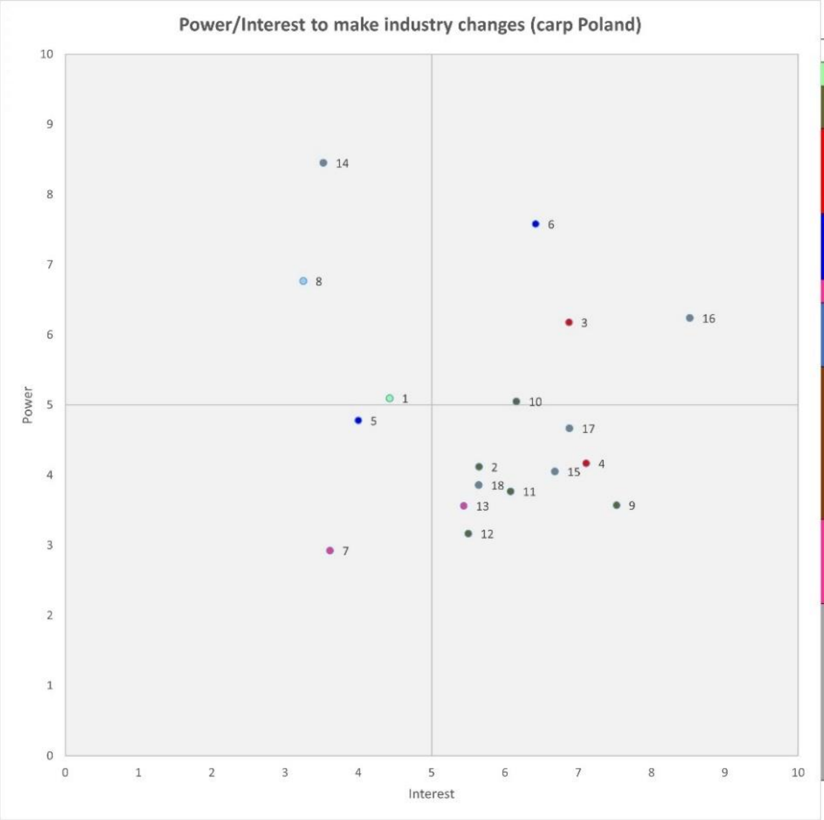
- *Higher production costs.*
- *Low carp prices due to limited season window (Christmas sales).*
- *Low carp prices due to imports of carp.*
- *Environmental challenges leading to welfare and performance issues.*
- *Environmental challenges leading to lack of water resources.*
- *Regulations on production volume.*

In round one we asked if current provincial (voivodeship) legislation is supporting the sustainable growth of the Polish carp aquaculture industry. Respondents had no opinion in terms of provincial legislation to support sustainable practices, while respondents indicate to disagree/no opinion regarding provincial legislation supporting the growth of the industry (graphs below, red bar). Additional, respondents clearly disagreed that national legislation support the sustainable growth of the industry. What topic should legislation (provincial/national) be focussed on increase financial margins and to promote carp as being low impact.



- *Legislate on environmental footprint, e.g., carbon.*
- *Fish processing.*
- *Financial instruments (e.g., subsidies, incentives, tax benefits) for innovations.*
- *Increase the amount of land available to farm carp.*
- *Organic certification.*
- *Other certification.*
- *Less regulation on production output.*
- *Supporting regulations to protect carp ponds as an environmental asset.*

During the value chain survey, participants were asked to score power/interest of other stakeholders towards making an industry change/innovation. These values were grouped in a stakeholder grid to find patterns of stakeholders with high interest and high power most likely to initiate industry changes (graph below). Barriers for innovation can be found in the low interest and high-power grid, or high interest and low power grid. For the Polish carp industry, respondents indicate that the industry innovation is not stakeholder led. How can the industry become better industry led?



Nodes	No.	Stakeholder
Grow-out	1	Farms
Feed (Ingredients)	2	Feed companies
Processing	3	Slaughter house and primary processing
	4	Value addition processing
Trade	5	Important and trading company
	6	Retail company
Equipment	7	Transport
Health	8	Vet/Health management company
Education	9	Education
	10	Recreational (guide) tour
	11	Research and innovation company (R&D)
	12	Trainer institution
Equipment	13	Equipment producer, maintenance and recycling
Third parties	14	Government and representative authorities
	15	Certification body/organization
	16	NGO
	17	Carp associations
	18	Consumer group

- *Increase the power of processors to make industry changes.*
- *Increase the interest of government and representative authorities to innovate the industry.*
- *Increase the power and interest of farms to innovate the industry.*
- *Increase the power of education and research to drive innovation.*
- *Increase the power of certifiers to set a standard and drive innovation.*

APPENDIX 2: COMMODITY TRADE AND BY-PRODUCT APPLICATION YIELDS

More details available in the GAIN report “*Valorisation of fish by-products*” (Malcorps *et al.*, 2020).

A2.1 Atlantic salmon commodities

Table A2.1: Selected Atlantic salmon commodities (FAO, 2020).

Commodity
Atlantic and Danube salmons, fresh or chilled
Atlantic salmon and Danube salmon, frozen
Salmon fillets, dried, salted or in brine
Salmon fillets, fresh or chilled
Salmon fillets, frozen
Salmon minced, prepared or preserved
Salmon nei, not minced, prepared or preserved
Salmonoids meat, fresh or chilled, nei
Salmonoids nei, minced, prepared or preserved
Salmonoids, fresh or chilled, nei
Salmonoids, frozen
Salmonoids, not minced, prepared or preserved
Salmons, fresh or chilled, nei
Salmons, live
Salmons, salted or in brine
Salmons, smoked

A2.2 Rainbow trout commodities

Table A2.2: Selected rainbow trout commodities (FAO, 2020).

Commodity
Trout fillets, fresh and chilled
Trout fillets, frozen
Trouts and chars live
Trouts and chars, fresh or chilled
Trouts and chars, frozen
Trouts and chars, smoked

A2.3 Gilthead seabream commodities

Table A2.3: Selected gilthead seabream commodities (FAO, 2020).

Commodity
Gilt-head seabream, fresh or chilled
Gilt-head seabream, frozen

A2.4 European seabass commodities

Table A2.4: Selected European seabass commodities (FAO, 2020).

Commodity
Seabass, fresh or chilled
Seabass, frozen

A2.5 Common carp commodities

Table A2.5: Selected common carp commodities (FAO, 2020).

Commodity
Carps live
Carps, eels and snakeheads, fillets, fresh or chilled
Carps, eels and snakeheads, fillets, frozen
Carps, fresh or chilled
Carps, frozen

A2.6 Turbot commodities

Table A2.6: Selected turbot commodities (FAO, 2020).

Commodity (Commodity)
Turbot, fresh or chilled
Turbots, frozen

A2.7 FPH yields from by-products

Table A2.7: FPH yields from by-products (provided by IIM-CSIC).

Species/by-product (100 kg)	Yield/100kg				
Output	**Hydrolysate (L)**	**Wet bones (kg)**	**Fish oil (L)**	**Concentrate FPH (L)**	**FPH (kg)**
Atlantic salmon heads	177	10.7	11.5	35.4	12
Atlantic salmon trimmings (20%) and frames (80%)	180	10.2	9.5	36	14
Rainbow trout heads	178	10	9.4	35.6	11.8
Rainbow trout trimmings (10%) and frames (90%)	179	9.5	10.7	35.8	11
Turbot heads	185	16.8	0.3	37	12
Turbot trimmings (15%) and frames (85%)	180	16.4	4.3	36	14.6

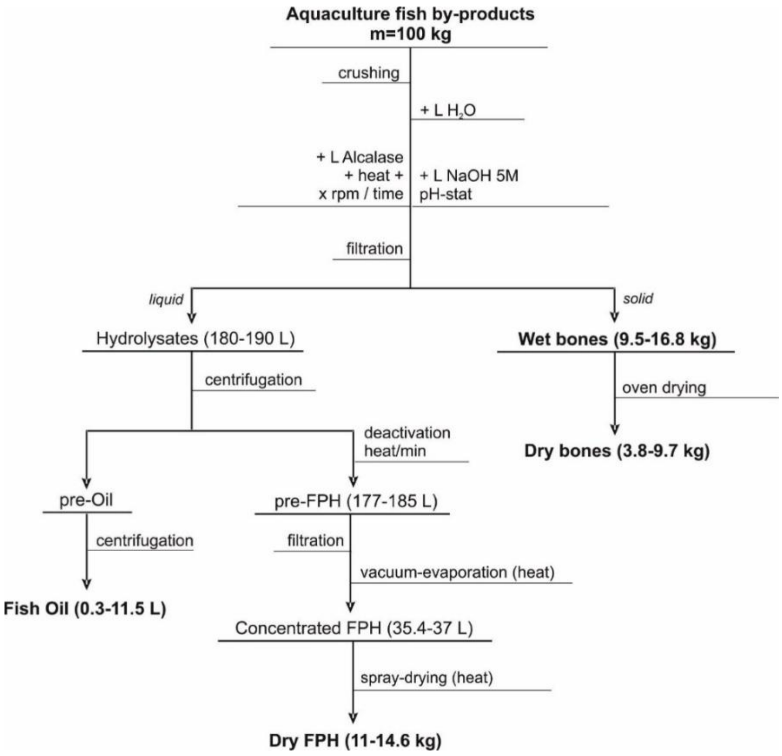


Figure A2.7: Flow chart of FPH production (provided by IIM-CSIC).

A2.8 Peptone yields from by-products

Table A2.8: Peptone yields from by-products (provided by IIM-CSIC).

Species/by-product (100 kg)	**Yield/100 kg**		
	Wet bones (kg)	**Fish oil (L)**	**Dry peptone (kg)**
Atlantic salmon heads	10.5	11.5	12
Atlantic salmon trimmings (20%) and frames (80%)	10.2	10.5	13
Atlantic salmon viscera	0	15	11
Rainbow trout heads	10	10	11.8
Rainbow trout trimmings (10%) and frames (90%)	9.5	10.7	11
Rainbow trout viscera	0	14	11
Turbot heads	16.8	0.3	12
Turbot trimmings (15%) and frames (85%)	16.4	4.3	14.6
Turbot viscera	0	2	12.5
Gilt-head seabream heads	19.9	5.9	11
Gilt-head seabream trimmings (13%) and frames (87%)	14	10.6	12.7
Gilt-head seabream viscera	7.3*	3.9	7
European seabass heads	19.2	8.1	11.4
European seabass trimmings (16%) and frames (84%)	10.6	13.8	10.5
European seabass viscera	0	27.5	6

**Assumed due to contamination*

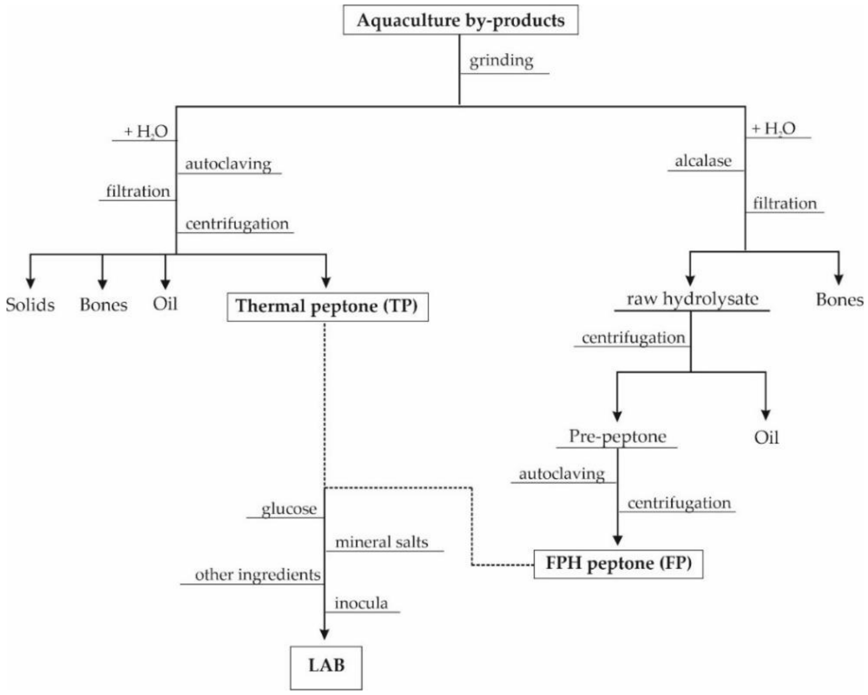


Figure A2.8: Flow chart of peptone production used for producing lactic acid bacterium (LAB) (provided by IIM-CSIC)

A2.9 Gelatine yields from by-products

Table A2.9: Gelatine yields from by-products (provided by IIM-CSIC).

Species/by-product (100 kg)	**Treatment**	**Yield/100 kg**	
		Concentrated gelatine (L)	**Gelatine (kg)**
Turbot skin	By chemical (at room temperature) and thermal processing	50	5.2
Turbot skin	By chemical (at 4^0C) and thermal processing	50	8.2
Salmon Skin	by chemical (at room temperature) and thermal processing	50	4.7

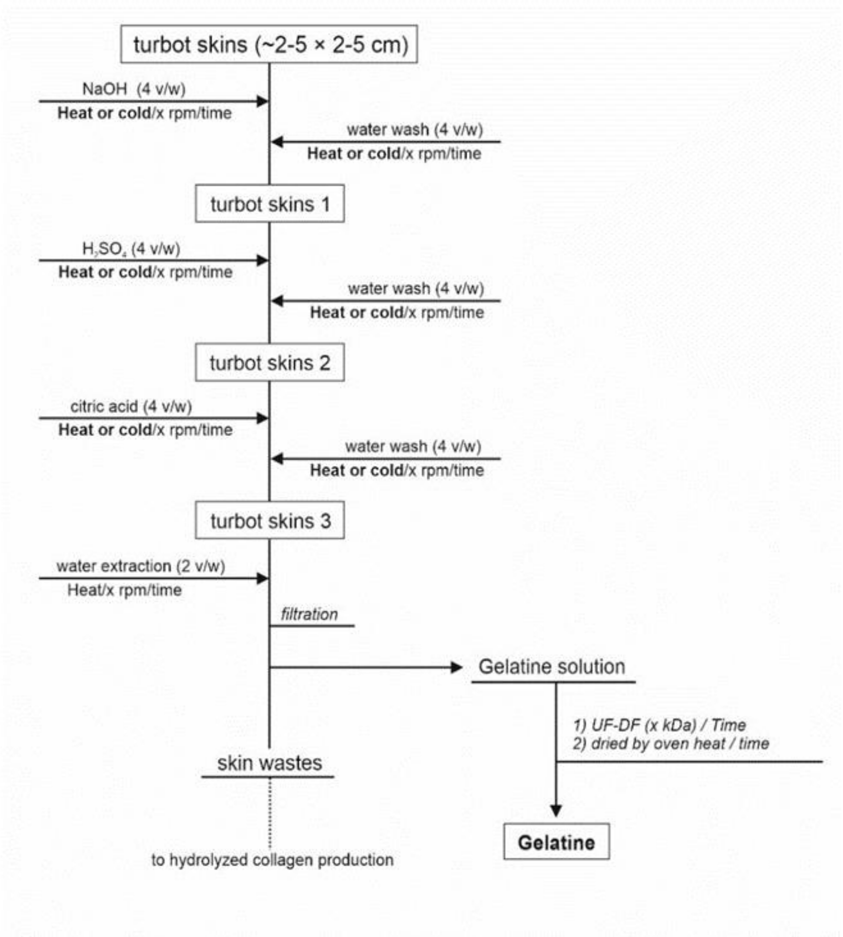


Figure A2.9: Gelatine production process from turbot (provided by IIM-CSIC).

A2.10 Collagen yields from by-products

Table A2.10: Collagen yields from by-products (provided by IIM-CSIC).

Species/by-product (100 kg)	**Yield/100 kg**	
Output	**Dialyzed (L)**	**Collagen (kg)**
Turbot skin	2260	17.7
Atlantic salmon skin	400	5.34

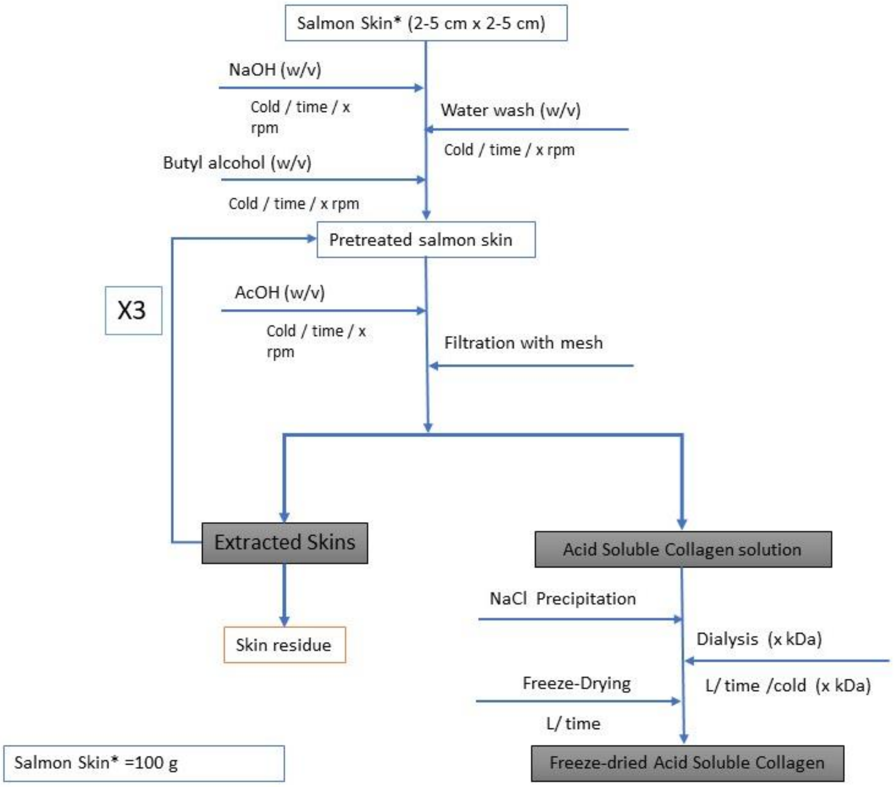


Figure A2.10 Collagen production process (provided by IIM-CSIC).

APPENDIX 3: LIFE CYCLE INVENTORIES OF AQUAFEED INGREDIENTS

A3.1 LCI marine ingredients mix for FM

Table A3.1: LCI marine ingredients mix for FM. Mix of whole fish and by-products based on the Skretting Environmental Footprint Report (2019). Assumed most fish (and by-products) landed locally in Norway, assume no transport for these ingredients to the feed mill. LCI inventory of the individual ingredients and their respective resource inputs available in appendix A, supplementary data in Newton et al. (2022).

	Quantity	**SD95**	**Notes**
INPUTS			
-Anchoveta standard (FAQ) meal at plant (PE), kg	61	Undefined	
-Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	641.95		-Transport from cabo blanco (Peru) to Bergen (Norway). 1000kg / 61 kg = 16.4 10528km / 16.4 = 641.95 tkm
-Blue Whiting standard (FAQ) and prime meal at plant (NO), kg	259	Undefined	
-Capelin standard (FAQ) and prime meal at plant (NO), kg	1		
-Herring (Atlantic) standard (FAQ) and prime meal at plant (NO), kg	80		
-Gulf Menhaden standard (FAQ) and prime meal at plant (US), kg	23		
-Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	143.33		-Transport from New York (USA) to Bergen (Norway). 1000kg / 23 kg = 43.48 6231.98km / 43.48 = 143.33 tkm
-Horse (Atlantic) mackerel standard (FAQ) and prime meal at plant (ES), kg	2	Undefined	
-Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	6.73		-Transport from Port of Algeciras (Spain) to Bergen (Norway). 1000kg / 2 = 500 3363.23km / 500 = 6.73 tkm

-European sprat standard (FAQ) and prime meal at plant (NO), kg	37	Undefined	-Substituting Norway Pout
-Sandeel standard (FAQ) and prime meal at plant (DK), kg	148		
-Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	118.63		-Transport from Port of Aarhus (Denmark) to Bergen (Norway). 1000kg / 148 kg = 6.76 801.92 / 6.76 = 118.63
-European sprat standard (FAQ) and prime meal at plant (NO), kg	173	Undefined	-In place of sprat + Baltic sprat + others
- Capelin by-product standard (FAQ) meal at plant (NO), kg	1		
-White fish (cod, haddock, saithe) by-products standard (FAQ) meal at plant (NO), kg	20		
-Herring (Atlantic) by-product standard (FAQ) meal at plant (NO), kg	127		
-Horse (Atlantic) mackerel by-product standard (FAQ) meal at plant (ES), kg	1		
-Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), kg	3.36		-Transport from Port of Algeciras (Spain) to Bergen (Norway). 1000kg / 1 = 1000 3363.23km / 1000 = 3.36323 tkm
-Mackerel (Atlantic) by-product standard (FAQ) meal at plant (NO), kg	43	Undefined	
-White fish (cod, haddock, saithe) by-products standard (FAQ) meal at plant (NO), kg	9		Substituting pollock
-European sprat by-product standard (FAQ) meal at plant (NO), kg	16		-Substituting sprat and other trimmings
OUTPUTS		Allocation %	
-Fishmeal (FAQ) based on Skretting mix of whole fish and by-products at feed mill Norway*, kg	1000	100	

A3.2 LCI marine ingredients mix for FO

Table A3.2: LCI marine ingredients mix for FO. Mix of whole fish and by-products based on the Skretting Environmental Footprint Report (2019). Assumed most fish (and by-products) landed locally in Norway, assume no transport for these ingredients to the feed mill. LCI inventory of the individual ingredients and their respective resource inputs available in appendix A, supplementary data in Newton et al. (2022).

	Quantity	**SD95**	**Notes**
INPUTS -Anchoveta standard (FAQ) oil at plant (PE), kg -Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	385 4049.23	Undefined	-Substituting anchovy + Pacific anchoveta -Transport from cabo blanco (Peru) to Bergen (Norway). 1000kg / 385 kg = 2.6 10528km / 2.6 = 4049.23 tkm
-Blue Whiting standard (FAQ) and prime oil at plant (NO), kg -Herring (Atlantic) standard (FAQ) and prime oil at plant (NO), kg -Gulf Menhaden standard (FAQ) and prime oil at plant (US), kg -Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	68 85 84 523.7	Undefined	-Herring + Araucanian Herring -Transport from New York (USA) to Bergen (Norway). 1000kg / 84 kg = 11.9 6231.98km / 11.9 = 523.7 tkm
-European sprat standard (FAQ) and prime oil at plant (NO), kg	148 92		Substituting Norway pout, Chilean jack mackerel, sprat, and Baltic sprat

-Sandeel standard (FAQ) and prime oil at plant (DK), kg -Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	73.77		-Transport from Port of Aarhus (Denmark) to Bergen (Norway). 1000kg / 92 kg = 10.87 801.92 / 10.87 = 73.77
-Sardine standard (FAQ) and prime oil at plant (ES), kg -Transport, freight, sea, transoceanic ship {GLO}| market for | APOS, U (boat to Norway), tkm	16 53.81		-Sardine from Spain substituted sardine from Mauritania + others -Transport from Port of Algeciras (Spain) to Bergen (Norway). 1000kg / 16 = 62.5 3363.23km / 62.5 = 53.81 tkm
-White fish (cod, haddock, saithe) by-products fish oil at plant (NO), kg -Herring (Atlantic) by-product standard (FAQ) oil at plant (NO), kg -Mackerel (Atlantic) by-product standard (FAQ) oil at plant (NO), kg -European sprat by-product standard (FAQ) oil at plant (NO), kg	2 64 46 11		-Substituting sprat and trimmings others

OUTPUTS -Fish oil (FAQ) based on Skretting mix of whole fish and by-products at feed mill Norway*, kg	 1000	Allocation % 100	

A3.3 List of standard LCIs (ingredients) in Agri-footprint and Ecoinvent

Table A3.4: List of standard LCIs in Agri-footprint and Ecoinvent of ingredients. Also included is the energy use of feed mills constructed by primary data collection from a feed producer in Norway. This data was obtained through an iterative process and converted to produce 1000 kg feed formulation produced at the feed mill.

	Quantity	**SD95**	**Notes**
INPUTS			
-Blood meal, spray dried, from blood processing, at plant/NL Economic, kg	Variable	Undefined	
-Maize gluten meal, from wet milling (gluten drying), at plant/DE Economic, kg			
-Poultry meal, from dry rendering, at plant/NL Economic, kg			
-Soybean meal {GLO}| market for | APOS, U, kg			
-Soy protein concentrate, consumption mix, at feed compound plant/NL Economic, kg			
-Wheat gluten meal, from wet milling, at plant/NL Economic, kg			
-Wheat grain, market mix, at regional storage/DE Economic, kg			
-Wheat flour, from dry milling, at plant/UK Economic, kg			
-Crude rapeseed oil, from crushing (solvent), at plant/NL Economic, kg			
-Dicalcium phosphate, processing/FR U			
-Vitamin, animal feed, at retailer gate/FR U, kg			
-L-Lysine HCl, processing/FR U, kg			
-DL-Methionine, processing/RER U, kg			
Feed mill plant Bergen (Norway)*			
Feed mill 1, energy input per kg feed	333.33		
-Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region | APOS, U, kWh per 1000 kg	101.17	Lognormal: 1.05	
-Natural gas, from onshore and offshore prod. incl. pipeline and LNG transport, consumption mix, EU-27 S System - Copied from ELCD, kg per 1000 kg	14.58	Lognormal: 1.05	

-Liquefied petroleum gas {RoW}| market for | APOS, U, kg per 1000 kg	0.94	Lognormal: 1.05	
-Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery | APOS, U, MJ per 1000 kg	2.89	Lognormal: 1.05	
-Feed mill 2, energy input per kg feed	333.33		
-Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region | APOS, U, kWh per 1000 kg	229	Lognormal: 1.05	
-Tap water {Europe without Switzerland}| market for | APOS, U, ton per 1000 kg	0.533	Lognormal: 1.05	
-Emissions to air: carbon dioxide, kg per 1000kg	28		
-Feed mill 3, energy input per kg feed	333.33		
-Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region | APOS, U, KwH per 1000 kg	229	Lognormal: 1.05	
-Tap water {Europe without Switzerland}| market for | APOS, U, ton per 1000kg	0.541	Lognormal: 1.05	
-Emissions to air: carbon dioxide, kg per 1000kg	50		
OUTPUTS		Allocation %	
Feed formulation, kg	1000	100	

[*] *Inputs are displayed per 1000kg. However, 3 feeds mills are included to cover the variability in inputs across different sort and scales of feeds mills. Therefore, while modelled in SimaPro, each input is divided by 3, as each feed mill input is 333.33 kg.*