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The Pacific oyster *(Magallana gigas)*:
Can an invasive alien species be used as a sustainable and profitable novel ingredient in salmon feed?

Stillehavsøsters *(Magallana gigas)*:

Kan en invaderende fremmed art være en bærekraftig og lønnsom ny ingrediens i laksefôr?

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Bioeconomy - Bio-based value creation and business development

The world is your oyster – an AI generated picture using DALL·E.

Preface

This master's thesis marks the end of seven years in academia where I have been exposed to challenges of different academic nature. This thesis is no exception, and I would like to express my deepest gratitude to my supervisors, Erlend Dancke Sandorf and Trond Kortner, who has gracefully guided me through the preparation of this multidisciplinary thesis. Thank you, Erlend, for all the motivation and honest feedback. Your genuine interest is contagious, and it has been a true joy to discuss my thesis with you. Thank you, Trond, for all your thorough feedback, for helping me understand all the complexities in feed production and for always having a friendly smile.

I would like to make a special mention of Petter Bjørge from Storm Østers AS who paid for all the analyses carried out by NMBU in connection with this study, participated in the interview and was available throughout the process. I am deeply grateful for all his insights. I am rooting for him and wish him great success with his oyster adventure. I would also like to extend my gratitude to Øystein Ahlstrøm at the Faculty of Biosciences at NMBU, for helping me understand nutrient composition and digestibility, as well as their place in feed formulation. Åsa Strand at IVL Swedish Environmental Research Institute and her former student, Mathilda Nyquist, have been very helpful in the preparation of this thesis. Åsa has been available to me throughout the process and has contributed with her vast knowledge of oysters. Mathilda has written a great thesis on the use of the Pacific oyster in feed and has readily shared with me the analysis of her own data on the nutrient composition of oysters. I am grateful to the feed company representatives for taking time out of their busy schedules to meet with me and share their valuable knowledge. NMBU university library helped me in formulating the search strings in the systematic literature search and getting access to articles. I would like to thank Mette Müller for being a driving force in accelerating the oyster project at NMBU and for making me believe in myself. I am also very grateful to Thore Larsgård, who has been a great support during my master's studies.

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Happy reading!

Lise Lotte Ås, 13.05.2023

Abstract

The uncertainties regarding sustainability of feed ingredients used for the farming of Atlantic salmon (*Salmo salar)* are receiving increasing attention from stakeholders and policy makers. At the same time, the Pacific oyster (*Magallana gigas*) has invaded the Norwegian coast, potentially threatening local biodiversity and the continuation of ecosystem services. The aim of this thesis was to provide a broad basis for assessing the opportunities and challenges of using the Pacific oyster as an ingredient in salmon feed. This was done to potentially mitigate the negative impacts of other commonly used feed ingredients such as fish meal and soy protein concentrate, while at the same time contributing to the management of an invasive alien species.

To achieve this, the thesis includes a systematic literature review about the implications on sustainability from the invasion of the Pacific oyster and from common salmon feed ingredients. Semi-structured interviews were conducted with a representative from each of the four main salmon feed production companies in Norway, in addition to Petter Bjørge from the oyster harvesting company Storm Østers AS. It contains an analysis of the nutrient comparison of the dried Pacific oyster meal, soy protein concentrate and fish meal. The digestibility of the dried oyster meal was evaluated in a feeding trial using mink (*Neovison vison*) as a model animal for salmon, and compared with digestibility coefficients of soy protein concentrate and fish meal.

On a dry matter basis, the Pacific oyster consisted of 49.3% crude protein, 20.4% ash, 8.2% fat and 0.71% EPA+DHA. When compared to requirement estimates of essential amino acids for salmon, the first limiting essential amino acids were phenylalanine and tyrosine, followed by methionine+cysteine, histidine and lysine. The apparent digestibility coefficient of crude protein was 79.5%. The nutrient profile was considered interesting but not optimal by the feed producers interviewed. The price per tonne dried oyster meal is 825,688 NOK, a price that, at present, does not allow the Pacific oyster to compete on the market with other common salmon feed ingredients. The harvesting capacity of Storm Østers AS was estimated to allow for the annual production of 26.5 tonnes of dried oyster meal, which is an insufficient volume to satisfy the smallest annual requirement of salmon feed producers. Compared to the sustainability profile of soy protein concentrate and fish meal, the Pacific oyster harvesting comes with a favourable sustainability profile that allows for the continuation of ecosystem services in the harvested areas, with some uncertainties related to energy use while harvesting and processing. During the preparation of this thesis, it was discovered that feed producers are not looking to reduce their reliance on common feed ingredients, particularly marine ingredients, limiting the potential of novel feed ingredients to have a mitigating effect on the current use of unsustainable ingredients.

Key words: novel feed ingredient, salmon feed, sustainability, biodiversity, Pacific oyster, cost, ecosystem services.

Sammendrag

Usikkerheten knyttet til bærekraften til fôringrediensene som brukes i oppdrett av laks (*Salmo salar*) får stadig større oppmerksomhet fra interessenter og beslutningstakere. Samtidig har stillehavsøsters (*Magallana gigas*) invadert Norges kyst og truer potensielt det lokale biologiske mangfoldet og opprettholdelsen av økosystemtjenester. Målet med denne oppgaven var å gi et bredt grunnlag for å vurdere mulighetene og utfordringene ved bruk av stillehavsøsters som ingrediens i laksefôr. Dette ble gjort for å potensielt redusere de negative virkningene av andre vanlige fôringredienser som fiskemel og soyaproteinkonsentrat, og samtidig bidra til forvaltning av en invaderende fremmed art.

For å oppnå dette inneholder oppgaven en systematisk litteraturgjennomgang av de konsekvensene invasjonen av stillehavsøsters og vanlige fôringredienser har på bærekraft. Semistrukturerte intervjuer ble gjennomført med en representant fra hver av de fire største laksefôrprodusentene i Norge, og Petter Bjørge fra østersselskapet Storm Østers AS. Den inneholder en sammenligning av næringsinnholdet i tørket stillehavsøstersmel, soyaproteinkonsentrat og fiskemel. Fordøyeligheten av det tørkede østersmelet ble evaluert i et fôringsforsøk med mink (*Neovison vison*) som modelldyr for laks og sammenlignet med fordøyelighetskoeffisienter for soyaproteinkonsentrat og fiskemel.

På tørrstoffbasis besto stillehavsøsters av 49.3% råprotein, 20.4% aske, 8.2% fett og 0.71% EPA+DHA. Sammenlignet med behovsestimat av essensielle aminosyrer for laks, var de første begrensende aminosyrene fenylalanin og tyrosin, etterfulgt av metionin+cystein, histidin og lysin. Den apparente fordøyelighetskoeffisienten for råprotein var 79.5%. Fôrprodusentene som ble intervjuet så næringsstoffprofilen som interessant, men ikke optimal. Prisen per tonn tørket østersmel er 825,688 NOK, en pris som for øyeblikket gjør det umulig for stillehavsøsters å konkurrere på det samme markedet som andre vanlige ingredienser i laksefôr. Høstingskapasiteten til Storm Østers AS ble anslått til å tillatte en årlig produksjon på 26.5 tonn tørket østersmel, noe som er et utilstrekkelig volum for å tilfredsstille det minste årlige behovet til laksefôrprodusenter. Sammenlignet med bærekraftprofilen til soyaproteinkonsentrat og fiskemel har høsting av stillehavsøsters en gunstig bærekraftprofil som gjør det mulig å videreføre økosystemtjenestene i høstingsområdene, men med noe usikkerhet knyttet til energibruk under høsting og prosessering. Under utarbeidelsen av denne oppgaven ble det funnet at fôrprodusenter ikke ønsker å redusere sin avhengighet av vanlige fôringredienser, særlig marine ingredienser, noe som begrenser potensialet for at nye fôringredienser kan ha en positiv effekt på bærekraften av dagens fôringredienser.

Nøkkelord: stillehavsøsters, nye fôringredienser, laksefôr, bærekraft, biodiversitet, økosystemtjenester, kostnader.

Contents

List of tables

List of figures

Abbreviations

IAS = invasive alien species
SPC = soy protein concentrate
LCPUFA = long chained polyunsaturated fatty acids
EPA = eicosapentaenoic acid
DHA = docosahexaenoic acid
LCA = life cycle analysis
FCR = feed conversion ratio
ADC = apparent digestibility coefficient
DM = dry matter basis
DW = dry weight

1. Introduction

1.1 Purpose, relevance and motivation

There is a pressing need to figure out how to feed a growing human population in a sustainable way. Because land-based animal food production has the greatest impact on climate, the greatest potential for increased food production lies in the oceans (FAO, 2018; Ritchie & Roser, 2020). However, there is a stagnation in wild fish populations due to overexploitation and unsustainable practices, but there is great potential for growth with farmed fish (FAO, 2018). According to Almås et al. (2020), one of the most efficient ways to produce animal protein is through aquaculture. In fact, aquaculture continues to be the fastest growing major food production service (FAO, 2018).

In 2020, the Norwegian farming of 1,5 million tonnes of Atlantic salmon (*Salmo salar*) required about 2 million tonnes of feed (Aas et al., 2022a). The farming of salmon is predicted to grow to 3 million tonnes by 2030 and to 5 million tonnes by 2050 (Aas et al., 2022a; Solberg et al., 2021). A yearly production of 5 million tonnes salmon will require about 6 million tonnes of feed (Almås et al., 2020). In salmon feed, soy protein concentrate (SPC) was the dominant plant protein source in 2020 with the total amount used being 413 611 tonnes (Aas et al., 2022a). In the same year, fish meal was the dominant marine protein source with a total amount of 239 711 tonnes. Unfortunately, there are several implications related to sustainability with the current salmon feed production. In fact, feed and fuel use are the largest contributors to emissions from the salmon industry (Pelletier et al., 2009; Ziegler et al., 2022). There has been an increased use of soy since the year 2000, which has led to further conversion of arable land, deforestation, increased use of fertilisers and fresh water and a decrease in the ability of developing countries to produce food for themselves (Aas et al., 2022; Caro et al., 2018; Darnton-Hill & Coyne, 1998: cited in Couture et al., 2019; Fehlenberg et al., 2017; Solomons, 2000: cited in Couture et al., 2019; Willaarts et al., 2011). At the same time, fish meal is known to impact both immediate and distant environments through increased energy consumption, nutrient emissions, fish stock depletion and climate change (Diana, 2009; Naylor et al., 2000; Pelletier & Tyedmers, 2007). Naturally, there is a great focus on increasing the sustainability of salmon feed, and there is growing interest from a wide range of stakeholders. While novel feed ingredients are an increasing research focus, it also has an increased political interest (Aas et al., 2022a; Regjeringen, 2021; Solberg et al., 2021; Wei et al., 2021). In the Norwegian government's policy statement "Hurdalsplattformen" it is stated that all feed ingredients should come from sustainable sources by 2030. Today, 0.4% of ingredients come from novel sustainable sources (Aas et al., 2022a).

Simultaneously, climate change and human activities are leading to increased introductions of invasive species (Mainka & Howard, 2010; J. A. McNeely, 2001). Invasive species are one of the greatest threats to biodiversity and human health (Brondizio et al., 2019; Pyšek et al., 2020). Additionally, the estimated annual cost of invasive aquatic species globally is $345 billion (Cuthbert et al., 2021). In Norway, there are currently about 1500 alien invasive species that can have negative effects on the ecosystems they invade (Miljøstatus, 2022). These include changing the structure of the natural habitats, reducing biodiversity by outcompeting native species, as well as introducing unwanted parasites and diseases (Miljødirektoratet, n.d.). There are invasive species that are labelled as “very high risk” due to their potential impact on the invaded ecosystem and their ability to disperse (Jelmert et al., 2018). Examples of invasive species categorised as “very high risk” in Norway are the Canada goose (*Branta canadensis*), sea vomit (*Didemnum vexillum*), king crab (*Paralithodes camtschaticus*) and Pacific oyster (*Magallana (former Crassostrea) gigas*). The Pacific oyster, a filter feeding mollusc, has since a few findings in 2006 in southern Norway, spread to most of the southern, eastern and western coast (Mortensen et al., 2022). The work to determine management options began in 2016 (Jelmert et al., 2020).

The Pacific oyster has the potential to alter the ecosystems it enters and change species composition (Buschbaum et al., 2016; Grabowski, 2004). A change in species composition can have cascading effects through the trophic levels in an ecosystem, potentially leading to a major change in ecosystem services (Bell et al., 2020; Flood et al., 2020). Ecosystem services are the way nature provides food, materials, pharmaceuticals, climate regulation, and even recreational and educational services (FAO, 2018; Millennium Ecosystem Assessment, 2005; TEEB, 2010). This highlights the importance of limiting the spread of invasive species. The impact of the Pacific oyster on Norwegian ecosystems remains uncertain, as the effects seems to vary with different substrate and local fauna (Markert et al., 2010; Reise, 1998; Troost, 2010). If there is insufficient knowledge of the effects associated with an invasive species, Norway is obliged by law to act in accordance with the precautionary principle (Naturmangfoldloven, 2023, § 9). However, there is scientific consensus that complete eradication of the Pacific oyster is highly unlikely (Hansen et al., 2022; Sambrook et al., 2014; Simberloff, 2021; Troost, 2010). This means it is important to develop strategies that can effectively control the spread of the Pacific oyster. According to Begon et al. (2006), management of an invasive species is expensive, and it can be challenging to locate the resources needed to limit the spread of the species. A recognised strategy to limit the spread of invasive species is finding a use for the resource and commercialise it (Giakoumi et al., 2019). The commercialisation of a species like the king crab is an example of a successful economic utilisation of invasive species in Norway. While being considered an immense threat to northern fishing grounds when first discovered in 1977, the king crab added an ex-vessel value of about 800 million NOK in 2022 (Fiskeridirektoratet, 2023; Miljøstatus, 2021).

Due to regulations seeking to limit the dispersal of the Pacific oyster, farming is prohibited and the Norwegian Pacific oysters are currently harvested by hand (Forskirft om akvakultur, 2023, § 4; Miljødirektoratet, 2016). When harvesting wild oysters, the oysters do not always have the qualities that make them suitable for the human market. They might be oddly shaped or too large. New technologies that harvest wild oysters are likely able to harvest all types of oysters, leaving us with a growing resource without a use. Additionally, the Pacific oyster is worth researching as a feed ingredient as it is a lower trophic species, meaning that they need much less energy to grow than higher trophic species such as fish (Pelletier & Tyedmers, 2007). Furthermore, harvesting wild oysters does not acquire added nutrients, water or arable land, nor does it contribute to a decrease in wild fish population, a common challenge with other feed ingredients (Diana, 2009; Naylor et al., 2000). Other molluscs, like the blue mussel (*Mytilus edulis*), have also been evaluated as a potential novel feed ingredient (Almås et al., 2020). However, a general challenge with novel ingredients is reaching the scale and cost-efficiency that is needed for it to have a significant impact in salmon feed (Almås et al., 2020; Jones et al., 2020; Øverland & Skrede, 2017; Sarker, 2023). On a dry matter basis, the blue mussel has a protein content of approximately 65% protein and 8% lipids (Almås et al., 2020).

Protein and lipids are the most sought-after macronutrient groups in the salmon feed industry today (Wang et al., 2018). Macronutrients differ from micronutrients such as vitamins and minerals by being required in larger amounts and are the major source of energy (FAO et al., 2022). Protein is the main ingredient in salmon feed, and in 2020 the average salmon feed contained 37% crude protein and 29.6% crude lipid (Aas et al., 2022a; NRC, 2011). Of the lipids, marine highly unsaturated omega-3 fatty acids (i.e. eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)), are of particular interest, both regarding the salmon's own requirements and from a consumer perspective, and were included at an average of 2.2% in the Norwegian salmon feed in 2020 (Aas et al., 2022a; Almås et al., 2020; Tocher et al., 2019).

The aim of this thesis was to provide a broad basis for evaluating the Pacific oyster as an ingredient in salmon feed and to identify the associated opportunities and challenges. The evaluation of the use of the Pacific oyster in salmon feed was being undertaken to potentially mitigate some of the negative consequences associated with other common feed ingredients by partially replacing them with the Pacific oyster, whilst at the same time contributing to the important management of an invasive species. The evaluation of the Pacific oyster as a new feed ingredient can potentially form the basis of a new business that will ultimately provide both economic and sustainability benefits. As an evaluation including the shell was considered beyond the scope of this thesis, only the meat of the Pacific oyster was evaluated. A systematic literature search, semi-structured interviews with feed producers and nutrient analysis was carried out to achieve this goal.

1.2 Problem statement, hypotheses and limitations

The main topic of this thesis can be stated as: can the Pacific oyster, an invasive alien species in Norway, be used as a sustainable and cost-effective novel ingredient in salmon feed? To answer this, the main topic has been divided into three subtopics: **i) sustainability**, **ii) nutrient profile and digestibility**, and **iii) cost**.

i) sustainability

A literature search was conducted to answer the question related to sustainability: *Will the use of Pacific oysters as a raw material in salmon feed positively impact sustainability?* To answer the question of how the Pacific oyster affects the sustainability of salmon feed, it is natural to look at what kind of damage is limited by reducing the spread of the Pacific oyster. There was an examination of what impacts are mitigated by the use of Pacific oysters in place of the two most common protein sources in salmon feed: fish meal and SPC, both of which have problematic sustainability implications.

ii) nutrient profile and digestibility

To answer the question related to nutrient profile and digestibility: *Does the nutrient content and digestibility of the Pacific oyster relative to other commonly used feed raw material and* *the requirements of salmon make it an interesting raw material for feed producers?* An analysis of the macronutrient composition and digestibility of the Pacific oyster has been carried out. Micronutrients have been excluded from the scope of this thesis for the sake of workload limitation. The nutrient profile was provided in part by IVL Swedish Environmental Institute and the Department of Biosciences at the Norwegian University of Life Sciences. The nutrient profile was compared with two other commonly used ingredients in salmon feed: fish meal and SPC. Fish meal is the traditional protein source in salmon feed and SPC is the most widely used protein source today. These were chosen because the aim was to evaluate the Pacific oyster as a protein source. The amino acid profile was compared with the current knowledge of the amino acid requirements of salmon. As the Pacific oyster was being evaluated as a completely new ingredient in salmon feed, one employee from each of the four largest salmon feed producers in Norway was interviewed. They were asked to provide their insight into nutrient composition and general industry knowledge to highlight the opportunities and challenges of using Pacific oysters in salmon feed.

iii) cost

The initial aim was to find out whether *the cost of harvesting Pacific oysters was in line with what feed producers could pay*, but as comprehensive and robust data proved difficult to obtain, another layer was added to the cost question: *Can the use of Pacific oysters in salmon feed be profitable on a larger scale in terms of cost savings?* Data for this part was obtained partly from interviews with Petter Bjørge at the oyster harvesting company Storm Østers AS and four representatives from feed production companies, in addition to using The Economics of Ecosystems and Biodiversity (TEEB) framework and The Millennium Ecosystem Assessment (MEA).

1.3 Hypotheses

H_1: The use of the Pacific oyster in salmon feed will have a positive impact on the sustainability of the feed.

H_2: The nutrient content and digestibility of the Pacific oyster makes it an interesting raw material for feed producers when compared with fish meal, SPC and the nutritional requirements of salmon.

H_3: The price of the Pacific oyster makes it economically viable to use in salmon feed.

H_4: There is a gain from substituting the use of SPC and fish meal with the Pacific oyster by ensuring the continuation of ecosystem services.

1.4 Scope limitations

While other aspects are important when evaluating novel feed ingredients, they are deemed beyond the scope of this thesis. These aspects are 1) measuring, evaluating and considering micronutrients, both in the Pacific oyster and requirements of salmon. 2) measuring, evaluating and proposing solutions regarding algal toxins in the Pacific oyster. Algal toxins are an important challenge with the use of all bivalve filter feeders in food or feed products and have to be carefully measured and considered. 3) a broader analysis of the environmental impact of harvesting the Pacific oyster. All life cycle analyses (LCAs) that exist on oysters today are done on oyster farming, leaving a lot of uncertainty regarding the environmental impact of oyster harvesting. Also, an LCA would make the impacts of harvested oysters more comparable with the impacts of other feed ingredients. 4) research that covers all the other standards a novel ingredient needs to meet before it becomes included in the feed. To mention some: health effects, storage and processing, and growth performance.

2. Background

2.1 Salmon feed

In 2020, Norway used 1,976,709 tonnes of feed to produce 1,467,655 tonnes of salmon (Aas et al., 2022a). Feed is the largest driver of costs and emissions in salmon aquaculture, an industry that is expected to grow (FAO, 2020). To limit costs and emissions, it is important to ensure efficient use of feed (Aas et al., 2022a). The feed must meet all the nutritional requirements of the salmon, ensure optimal health and have physical properties that allow it to be handled efficiently in the production system as well as in a farm setting. This means that the pellets need to be strong enough to withstand both transport and handling, while still being of sufficient quality for proper ingestion and digestion by the salmon (Aas et al., 2011). The biggest drivers for change in which feed ingredients are being used is availability and price, which is greatly affected by climate change and an increased interest in sustainability from consumers and governments (Aas et al., 2022a; Regjeringen, 2021).

2.2 Nutrient requirements of Atlantic salmon

In 2020, the salmon feed used in Norway was composed of 37% protein and 29.6% fat, which gives an idea of the protein and fat requirements of salmon (Aas et al., 2022b).

Atlantic salmon has a high requirement for *protein*, and SPC was the dominant plant protein source in 2020 with the total amount used being 413,611 tonnes (Aas et al., 2022a). In the same year, fish meal was the dominant marine protein source with a total amount of 239,711 tonnes. Proteins are made up of amino acids and have multiple physical and metabolic functions (NRC, 2011). Some proteins have structural functions, such as providing stiffness to otherwise fluid components, and in connective tissues they provide connective components (Buxbaum, 2007). Many proteins are enzymes that are critical for biochemical reactions in the body. Proteins are also involved in cell signalling and immune responses. Amino acids have different properties due to variations in the structure of different R groups. In addition to being the building blocks of protein, amino acids are important in forming many coenzymes, neurotransmitters, hormones and other molecules. The amino acids that an organism cannot synthesise itself are known as essential amino acids (EAA), and these must be supplied in the diet (NRC, 2011).

Lipids, the main source of energy, have very varied roles in an organism, and are grouped together solely on the basis of their hydrophobic nature (NRC, 2011). While all fatty acids can provide energy to an organism, there are some long chain polyunsaturated fatty acids (LC-PUFA) that have essential roles in metabolism. Animals are generally unable to de novo synthesise PUFAs, which are therefore regarded as essential nutrients that must be provided in the diet. In relation to salmon feed the LC-PUFAs eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) are also considered essential dietary nutrients to ensure optimal growth (Bou et al., 2017; Ruyter, 2000).

Carbohydrates are a term for polyalcohol molecules with one or more aldehyde or ketone functions that are primarily composed of carbon, oxygen and hydrogen (NRC, 2011). While carbohydrates are a major component of the human diet, salmon do not digest carbohydrates well (Aas et al., 2022a; NRC, 2011; Villasante et al., 2019). Feeding carbohydrate-rich diets to salmon has been shown to reduce growth (Villasante et al., 2019). At the same time, the addition of digestible carbohydrates can provide metabolites to aid in the synthesis of important compounds, and are being used to achieve desirable physical properties of pellets (Aas et al., 2022a; Wilson, 1994). Today’s typical salmon diets contain about 10% carbohydrates in the form of starch.

Minerals are generally divided into micro- and macrominerals. Macrominerals are required at relatively high dietary intakes and are important for the formation of hard structures such as bones, teeth and scales (NRC, 2011). They are also important for electron transfer, pH regulation and osmoregulation. The most well-known macrominerals are calcium, chlorine, magnesium, potassium, sodium and phosphorus. Microminerals are generally required at a much lower concentration than macrominerals, consisting mainly of manganese, selenium, zinc, copper, iodine, iron and chromium. They are involved in various biochemical processes and are important components of hormones and enzymes (NRC, 1993).

In order to ensure optimal growth, reproduction and health, the organic compounds *vitamins* are required (NRC, 2011). These usually have to come from the diet and are divided into water-soluble and fat-soluble vitamins. Some of the water-soluble vitamins are mainly important as coenzymes, but some of them are also important as structural components. Fat-soluble vitamins such as A, D, E and K are absorbed together with dietary fat. They function mostly independent of enzymes, in processes such as cell differentiation, maintaining calcium homeostasis to aid in skeletal development and coagulation of blood. Several vitamins are also important for antioxidant function (NRC, 1993).

2.3 Digestibility

The term digestibility refers to the amount of nutrients that are absorbed by the organism; this is typically done by measuring the amount of nutrients that are ingested versus the amount that are expelled with the faeces (NRC, 2011). The bioavailability of nutrients is described by Mutanen (1986) in Andersen et al. (1997) as the amount of a nutrient that is absorbed by the organism and can be used in metabolism. Apparent Digestibility Coefficients (ADC) provide estimates of the digestibility of feed ingredients and can be used to select ingredients that will yield the best nutritional value at the lowest possible cost (Montoya-Mejía et al., 2016). Apparent digestibility differs from true digestibility in the sense that true digestibility includes the nitrogen from non-dietary sources such as cells and enzymes (Stein et al., 2007). The ADC usually employed for salmon feed used in Norway are 87% for protein, 90% for fat and 65% for carbohydrates (Hillestad et al., 1999)[1]. The level of digestibility can affect the environment as some of the nutrients expelled with the faeces will enter the ecosystem, possibly contributing to eutrophication (Folke et al., 1994). Therefore, the goal is to keep the digestibility as high as possible. Additionally, there are economic impacts when losing the nutrients that ideally should have been turned into salmon (Hillestad et al., 1999).

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[1] This info may be outdated, and efforts to obtain more recent research have been unsuccessful.

2.4 Common ingredients in salmon feed today

Over the last thirty years, there has been a massive change in the feed ingredients used in salmon diets. The amount of marine ingredients has gone from dominating the salmon diet at about 90% inclusion rate in 1990 to accounting for only about 23% in 2020 (figure 1) (Aas et al., 2022a). The marine ingredients have largely been replaced by vegetable ingredients. This change came from an increasing need for feed ingredients in a growing aquaculture sector, all the while catch from fisheries were stagnating (Sargent & Tacon, 1999). To reduce cost and increase supply, cheaper ingredients such as rapeseed oil and soybean meal have been taken into feed formulations (NRC, 2011). The most common ingredients in 2020 are respectively soy protein concentrate (20.9 %), rapeseed oil (18.0 %), fish meal (12.1 %), fish oil (10.3 %) and wheat gluten (9.8 %) (Aas et al., 2022a). Currently, the price per tonne of fish meal is 17,725.75 NOK and SPC costs approximately 9,000 NOK per tonne (Almås et al., 2020; IndexMundi, 2023). Fish meal has had a steep increase in price the last 20 years, while soybean meal has remined somewhat stable (figure 2)[2].

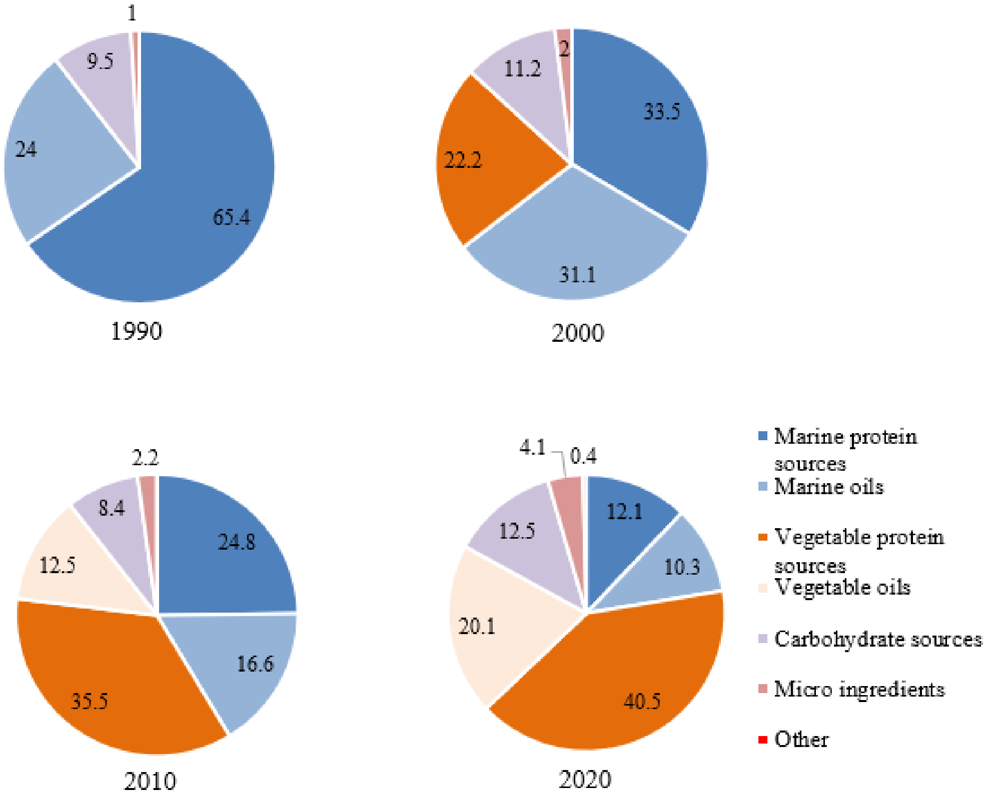

Figure 1 The change of feed ingredients used in salmon feed from 1990 to 2020. (Based on: Aas et al., 2022a).

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[2] This is a figure showing the price for soybean meal, which is another processed produced sourced from soybeans. Efforts to obtain the price development of soy protein concentrate have been unsuccessful.

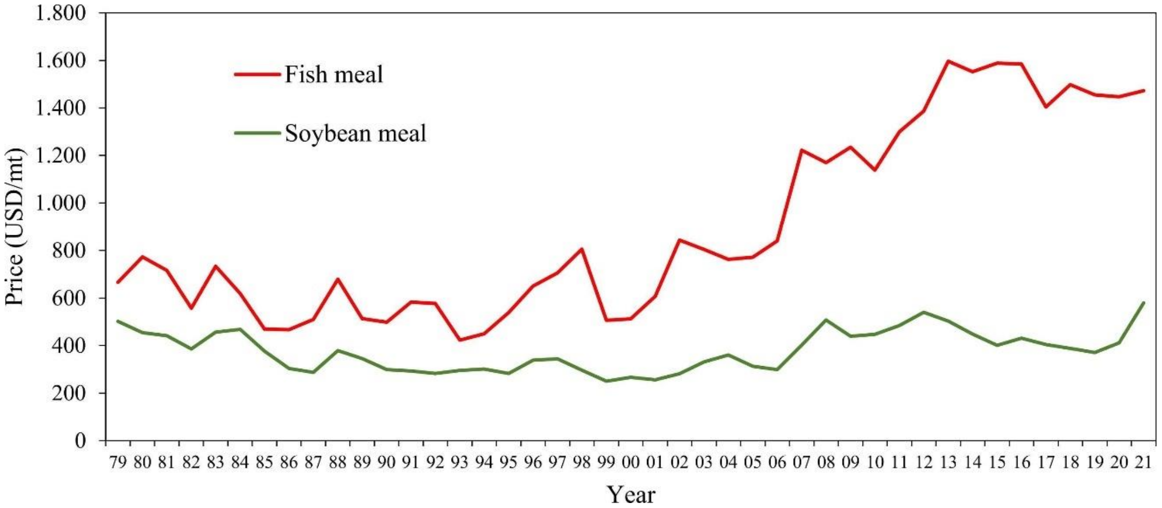

Figure 2 The nominal price development of fish meal and soybean meal the last 40 years (World Bank, 2020: cited in Nunes et al., 2022)

2.5 Current state of novel feed ingredients

Novel feed ingredients are an absolute necessity for future sustainable growth of salmon farming (Almås et al., 2020). Otherwise, most of the protein needs to be sourced from soy, an ingredient that has a lot of sustainability issues (Almås et al., 2020; Caro et al., 2018; Childers et al., 2011; Dalgaard et al., 2008; Willaarts et al., 2011). It is generally accepted that one of the main challenges with novel feed ingredients is to reach a scale that can significantly contribute to current and future feed use (Almås et al., 2020; Bellona, 2022; Valente et al., 2022). Another challenge is developing efficient and low-cost harvesting methods (Almås et al., 2020). Research is currently being carried out onto a wide range of species that may be suitable for use as salmon feed, including: seaweed, macro- and micro-organisms, insects, aquaculture of various marine organisms, plant by-products and animal by-products (Albrektsen et al., 2022; Bellona, 2022). While the most sought after feed ingredients are protein and omega-3 sources, some feed ingredients can bring added value through acting as attractors or increase digestibility of the feed (Almås et al., 2020). According to a report from Almås et al. (2020), there is large variation in the price for different feed ingredients, where crude protein is valued at between NOK 11–27 per kg and (pure) EPA/DHA between NOK 63–73 per kg. The most promising feed ingredients according to Almås et al. (2020) are pelagic and meso-pelagic fish. Mussels and shells are recognised as having potential to contribute <1% of the protein and EPA/DHA needs of the predicted growth in 2050. The report states that the theoretical potential for mussels and shells in 2050 are 4300 tonnes protein and 180 tonnes EPA/DHA. On the other hand, there is a lot of space available for cultivation and there is a good level of knowledge about the material. It is important to note that these figures are based on the blue mussel and does not include an evaluation of the Pacific oyster.

2.6 Invasive species

Invasive species, often called invasive alien species (IAS), are species that are introduced mainly by human activities to a habitat it has not previously occupied (Ojaveer et al., 2014; Simberloff, 2010). They differ from simply “alien species” in that they are deemed harmful to economies, environments or human health (Meyerson & Mooney, 2007). The human activities commonly causing IAS in marine environments are transfer of ballast water and cargo of internationally travelling ships and aquaculture practices (Ojaveer et al., 2015). An IAS have greater chance of successfully invading an area if there are a high availability of resources and appropriate physical conditions, such as a lack of natural enemies (Shea & Chesson, 2002). According to Begon et al. (2006) species aggregate when and where they find resources and conditions that favour reproduction and the findings of Rejmanek and Richardson (1996) suggests that species with a high rate of reproduction are more likely to successfully invade an ecosystem. In other words, if a species is transferred into a new ecosystem, it will fill the niches that are open. If the niches are occupied, it will compete with the species that occupies this niche. This means that in a species conservation perspective, the species that share the same niche with the invader should be the main focus of protection (Begon et al., 2006). Additionally, some species can modify the ecosystems it enters to better suit its own needs, allowing for greater dispersal and higher ability to compete for niches. Such species are called ecosystem engineers (Jones et al., 1997). Many molluscs are recognised as ecosystem engineers because they build substrate to obtain a habitat that better suit their own physical needs.

In many cases IAS has detrimental effects on the ecosystems they invade by negatively impacting biodiversity and ecosystem function (Mollot et al., 2017). IAS are one of the main challenges related to conservation of endangered species and have contributed to many species’ extinction (Simberloff, 2010). A well-functioning ecosystem is essential to ensure that an ecosystem is able to provide its services (Spangenberg et al., 2014). Ecosystem services maintain biodiversity and the production of ecosystem goods such as: food, fuel, timber, medicine and precursors for different chemicals (Daily, 1997). While it can be difficult to evaluate the monetary value of many ecosystems services, there have been many attempts to value the economic impact of IAS (Pejchar & Mooney, 2009; TEEB, 2010). In the US, the cost of IAS has been estimated at well over $100 billion per year due to increased conservation and management costs, as well as forage losses (Pimentel et al., 2005).

2.7 The Pacific oyster

The Pacific oyster, *Magallana gigas*, is a filter feeding mollusc, living attached to hard substrate along the shore (Dupuy et al., 1999). Its natural habitat includes open coastal ecosystems, rocky shores and mud flats. The Pacific oyster has few natural enemies, which has led to it being highly successful in invading large coastal areas (Troost, 2010). In its native habitat, the Pacific oyster is predated by crabs and flatworms (Parsons, 1974). The Pacific oyster is native to Japan and coastal regions of Asia, but has now spread to a number of countries in Africa, Australia, Europe and North- and South America (Troost, 2010). After being introduced to the Netherlands in 1964, the Pacific oyster was introduced for aquaculture purposes to all of Scandinavia in the seventies, and to Norway in 1979. The risk of further spread was thought to be low due to the limited ability of the oysters to reproduce at lower temperatures. However, since mid-2000, climate change has brought warmer summers and facilitated the spread of the Pacific oyster in Scandinavia (Wrange et al., 2010). While there are different findings regarding reproductive output, it is common that each oyster produces over 100 million eggs every reproductive cycle (Kang et al., 2003; Royer et al., 2008). Attempts have been made to determine the abundance of Pacific oysters along the Norwegian coast, but the findings have been inconclusive (Jelmert et al., 2020). The Pacific oyster was ranked 75th on the list of "100 worst alien species in Europe" due to the environmental impacts and habitat changes caused by its invasion (Nentwig et al., 2018). Although it can have negative environmental impacts, it has a high market value. It has been introduced into several countries for aquaculture purposes and has become the most farmed shellfish in the world (Houston et al., 2020). Due to regulations prohibiting farming of the Pacific oysters, the Norwegian Pacific oysters are currently harvested by hand (Forskirft om akvakultur, 2023, § 4;Miljødirektoratet, 2016).

2.8 What is sustainability?

Brundtland (1987) defined sustainable development as: *“development that meets the needs of the present without compromising the ability of future generations to meet their own needs”*(p. 37). Sustainability is often divided into “the three pillars of sustainability”: social, environmental and economic (Bardalen et al., 2020; Thomsen, 2013).

According to Brundtland (1987), s*ocial sustainability* refers to the rights of people to have their basic needs met and to realise their dreams of a better life, as long as this does not prevent other people, now or in the future, from doing the same. Brundtland's view of social sustainability includes how companies contribute to social sustainability through the way they produce their goods, and how they use and dispose of waste (Thomsen, 2013). Companies should limit the potential for a product to negatively impact an individual, including fair working conditions that respect human rights. According to Bardalen et al. (2020) the broader definition of social sustainability includes goals of welfare, social development and social structures. People should be included in the social, economic and political life of a community and not be discriminated against (Pierson, 2002: cited in Giovannoni & Fabietti, 2013). Furthermore, social sustainability indicates that the value created by a company should be distributed more evenly among stakeholders (Thomsen, 2013).

Bardalen et al. (2020) explains *environmental sustainability* as achieved when production and supplies essential for human health is sustained while the negative environmental impact is minimised, and the positive impact is increased. According to Thomsen (2013) businesses responsibility regarding environmental sustainability includes reducing a product’s energy consumption and packaging materials, increasing recycling and safely dispose of waste. This is supported by Potting et al. (2017), who states that regulations, standards and manufacturing practices are important for sustainability transitions. This can be achieved to a greater extent by utilising practises like reducing, reusing, repairing, refurbishing, remanufacturing, repurposing and recycling.

Economic sustainability ensures the continuation of production and social systems through investment, economic resilience, product quality and local economies, according to Bardalen et al. (2020). Economic activity is the production of goods and services to meet people's needs through the use of labour, natural resources and financial resources. According to Thomsen (2013) a growing economy is only sustainable if it contributes to improved human quality of life and environment. Economic sustainability has also been defined as corporations responsibility of ensuring well-being for future generations through a use of resources that are below the natural reproduction or the rate of development of substitutes (Dyllick & Hockerts, 2002). Additionally, they should not cause emission at a rate that cannot be reabsorbed by the environment, and they should not cause degradation in ecosystem services.

The sustainability definition put forward by Brundtland (1987) was further developed by the UN and launched as the sustainable development goals in 2017 (The United Nations, n.d.). The UN Sustainable Development Goals (SDGs) are 17 goals that act as a call for action to ensure prosperity for people and the planet, now and in the future.

Minimizing the use of unsustainable feed ingredients are closely linked to several of the SDGs: no. 2 zero hunger, no. 12 responsible consumption and production, no. 13 climate action, no. 14 life below water and no. 15 life on land (The United Nations, 2022).

SDG 2: *zero hunger*: Ensuring that feed ingredients come from sustainable sources can help strengthening both present and future food security (Ahmad et al., 2022; Van Huis, 2013). Limiting the use of soy and wild fish in salmon feed can contribute to an increased ability for developing countries in feeding themselves (Troell et al., 2014).

SDG 12: *responsible consumption and production*: Ensuring an as high as possible nutrient uptake from feed ingredients, will decrease the unsustainable loss of produced feed. Using local ingredients, such as the Pacific oyster in salmon feed, can limit the impact of transport (Pelletier & Tyedmers, 2007). Furthermore, an increased use of soy is connected to increase in the use of fertilizer (Cadillo-Benalcazar et al., 2020). Fertilizer has both environmental impacts and by substituting soy with the Pacific oyster, there is less impact from the use of fertilizer in salmon feed.

SDG 13: *climate action*: Currently, the greenhouse gas emissions related to farmed fish is lower than most land-based meat production (Ritchie & Roser, 2020). Reducing the impact of fish feed will allow the marine farmed proteins to become even less climate hostile than land-based meat production, as feed and fuel is responsible for most of the emissions in salmon farming (Pelletier et al., 2009; Ziegler et al., 2022).

SDG 14: *life below water*: Over-fishing is one of the biggest challenges related to capture fisheries (FAO, 2018). Limiting the use of wild fish in the salmon diet may aid in mitigating this issue. Furthermore, research shows that the invasion of the Pacific oyster can lead to a decrease in biodiversity in certain invaded areas (Green & Crowe, 2014). A sustainable management of the Pacific oyster can contribute to a decreased risk for eutrophication, while at the same time protecting the biodiversity in coastal ecosystems (Kotta et al., 2020).

SDG 15: *life on land*: There are major implications of using soy in salmon feed relating to land use change, biodiversity loss and deforestation (Caro et al., 2018; Fehlenberg et al., 2017; Voora et al., 2020; Willaarts et al., 2011).

3. Theory

Ecosystem services are closely linked to human well-being as they provide humans with food, medicine, water, climate change resistance and recreational opportunities (Fisher et al., 2009; Millennium Ecosystem Assessment, 2005). The protection of natural resources and the flow of ecosystem services requires the attention of decision-makers (TEEB, 2010). By assigning a monetary value to an ecosystem and quantifying the important services it provides, decision-makers can both be convinced of the value provided by an ecosystem and use this knowledge as an argument in decision-making processes (Daily et al., 2009). According to The Economics of Ecosystems and Biodiversity's (TEEB) report on Mainstreaming the Economics of Nature (2010) there are two main reasons for applying economic thinking to biodiversity and ecosystem services: to understand how human well-being depends on the services we receive from ecosystems, and to understand why economics will be the building blocks of successful environmental protection. Drivers of biodiversity loss include pollution, invasion of IAS and climate change, but ignoring the economic value of biodiversity and ecosystems is a major factor in their continued loss and destruction (Mazor et al., 2018; Millennium Ecosystem Assessment, 2005; TEEB, 2010). However, the TEEB (2010) report highlights the somewhat missing link between assigning an economic value to something and decision-makers taking action to manage it. This is supported by Millennium Ecosystem Assessment (2005), which states that there is a lack of supporting institutions for market mechanisms and economic instruments to work efficiently.

Even though decision-makers can be motivated to make precautionary decisions when provided with an economic value of the decision, few ecosystem services have explicit prices or are traded within an open market (TEEB, 2010). Some of the services can be priced in the market as they are directly valuable, called *provisioning services*, such as food, building materials, fresh water and precursors for pharmaceuticals (Millennium Ecosystem Assessment, 2005; TEEB, 2010). While services like *cultural services,* don't have a value assigned to them, they have in some cases been influential to political decisions due to being important to the public (TEEB, 2010). Cultural services are services such as recreational, ecotourism, aesthetic and spiritual (Millennium Ecosystem Assessment, 2005). Water purification is an example of a *regulating service* that, in recent years, has been assigned some monetary value and contributes to the total economic value of an ecosystem (La Notte et al., 2012; Piaggio & Siikamäki, 2021; TEEB, 2010). Other services that are recognised as regulating services aid in climate regulation, flood prevention, erosion regulation and water quality (Millennium Ecosystem Assessment, 2005). These are, however, often overlooked, or not noticed by society, as the effect of losing this service often falls on future generations or poor households (TEEB, 2010). The production of ecosystem services is aided by *supporting services*, such as nutrient cycling, photosynthesis and soil formation (Millennium Ecosystem Assessment, 2005). According to Millennium Ecosystem Assessment (2005), the provisioning services provided by aquaculture has an increasing productivity. At the same time, fresh water is in decline due to unsustainable use by both industry and private actors. There is also a decrease in water purification and natural hazard regulation.

To ensure human well-being in the future, it is important to maintain stocks of natural capital to enable the sustainable provision of flows of ecosystem services. It is important to understand how ecosystems function and how they can be affected by external and internal pressures. In this context, the issue of ecosystem resilience is important. This refers to the ability of ecosystems to withstand change and continue to provide services under challenging conditions (Côté & Darling, 2010; TEEB, 2010). Another definition of ecosystem resilience is its ability to return to a stable state after a disturbance (Gunderson, 2000). Some ecosystems are under so much pressure from climate change and human activity that they are closing into a threshold or tipping-point, a point where their ability to produce services might be greatly reduced (Reyer et al., 2015). According to Millennium Ecosystem Assessment (2005), when species are introduced to a new location, the services provided by that area are altered, the ability of the ecosystem to adapt to changing conditions is altered, and the impact of pathogens and pests is affected. As there is much uncertainty about the resilience of individual ecosystems, the precautionary principle must be applied to ensure the flow of ecosystem services into the future (TEEB, 2010).

The TEEB (2010) report includes an approach to recognize, demonstrate and capture the value of natural capital and ecosystem services.

Recognize value

In order to place a monetary value on an ecosystem service, the service must first be recognised (TEEB, 2010). Recognition in this case means to identify and assess the ecosystem services and their importance to different groups in society. In some cases, recognition of ecosystem services is sufficient to ensure sustainable use and conservation. This is often the case for services that are valued as spiritual or cultural.

Demonstrate value

Demonstrating value means that the value of the ecosystem services should be estimated and demonstrated with appropriate methods (TEEB, 2010). Demonstrating value can be done in economic terms to aid decision-makers in reaching a decision that considers the full cost and benefits of the ecosystem services (Liu et al., 2010; TEEB, 2010). Although they note that there is a lot of uncertainty regarding geographic and taxonomic scales, meaning that the costs are likely to be even higher, Haubrock et al. (2021) report a cost of $139.56 billion for IAS in Europe in 2020. Most methods of assigning value to an ecosystem considers the cost of change, rather than the total value of the ecosystem. The first step in valuation should be to identify all important changes in ecosystem services and to gather information on what, when and to whom these changes occur. According to Millennium Ecosystem Assessment (2005), utilising communities can be an important instrument in response to ecosystem degradation. Educating the community on the impacts of their actions can lead to behavioural changes that can lessen the negative impact on the ecosystem.

When demonstrating value, it is important to provide information on the monetary value of both tangible and intangible goods, as well as costs, including opportunity costs (TEEB, 2010). The valuation of ecosystem services can be complex, and in many cases the biological basis for economic valuation is poorly understood. The TEEB (2010) report recommends the use of an ecosystem services approach to economic valuation, taking into account the costs and benefits of both restoration and conservation. However, there is also a need to understand how ecosystems function. While biodiversity plays a key role in many ecosystem services, it also contributes to ecosystem resilience (Folke et al., 2004; Oliver et al., 2015). Efforts should be made to understand how resilient an ecosystem is, and this should be taken into account when calculating the total value of an ecosystem. Applying the precautionary principle in conservation will help to maintain the resilience of ecosystems. Akins et al. (2019) divides the precautionary principle into three: socio-cultural, environmental and economic. They advocate for the application of the precautionary principle to any activity that poses a threat of harm to the environment, cultures, human well-being and human communities, whether monetary or bioeconomic. Even if all causal links are not known, precautionary measures should be taken when such a threat is identified. This is supported by TEEB (2010), which states that if there is uncertainty about the resilience of an ecosystem or its value, decision-makers are urged to always act on the side of caution.

Capture value

The economic approach has a level known as *capturing value*, which aims to integrate ecosystem values into decision-making processes (TEEB, 2010). This can be done through incentives and pricing signals such as ecosystem service payments, providing tax breaks for conservation, or creating new business opportunities and markets for sustainably produced goods and services (Millennium Ecosystem Assessment, 2005; TEEB, 2010). It also highlights the alternative costs of inaction, showing that preventing biodiversity loss is much cheaper than restoring it.

The TEEB (2010) report recommends that companies should report on their own direct and indirect dependency and impact on ecosystem services in order to drive market change. To achieve this, governments should prioritise the development of a standardised methodology for companies to follow. In this regard, the term “externalities” is relevant. Externalities is defined as effects that occur when “a transaction between A and B has unwanted, positive or negative, consequences for third party” (Pigou, 1924 cited in: Andersen, 2007, p. 136). It is a powerful economic incentive in the principle “the polluter pays”, where the cost of externalities are internalised and liability is assigned (O'Connor, 1997). The EU has implemented a regulation making the polluter accountable when they unintentionally contribute to the invasion of a non-native species (Tollington et al., 2017). However, Genovesi et al. (2015) argues that it can be difficult to assign accountability and enforce sanctions due to the often cumulative and cascading effects of an introduction of an IAS, and the sometimes unclear link between IAS and polluter. Herein lies the need for strong institutions to enforce accountability and thorough knowledge of the function of ecosystems to understand the risks and locate the origin of an IAS (Millennium Ecosystem Assessment, 2005). A more thorough knowledge of ecosystem function and the risks of invasive species may also inhibit the spread of IAS (Lewis & Porter, 2014).

TEEB (2010) further suggests that biodiversity and ecosystem services should be integrated into product value chains, as this can lead to substantial cost savings and new revenues for companies, as well as improving their reputation. This is supported by Millennium Ecosystem Assessment (2005) which states that creating markets can increase the incentive for conservation. According to the Millennium Ecosystem Assessment (2005), technological advances have aided in decreasing the pressure on ecosystems, and will likely do so in the future. Promoting technologies that can increase yield, without increasing environmental impact, will decrease the risk of loss of biodiversity, due to decreasing the need for land conversion when there is a growing demand for food (Millennium Ecosystem Assessment, 2005; Trewavas, 2001).

4. Method

4.1 Systematic literature search

To approach the question of how including The Pacific oyster in salmon feed will impact sustainability in the salmon farming industry, a systematic literature review has been conducted. A systematic review is a process to identify, select, critically review and compile relevant research and to analyse the data found in this research (Higgins et al., 2019). To ensure an unbiased view of an issue, systematic reviews are conducted to identify all aspects of a topic, both positive and negative (Nightingale, 2009).

Creating optimised search strings

To ensure an optimised literature search and minimise bias, effort was put into understanding, creating and optimising questions by using a PICO table (Population, Intervention, Comparison and Outcome) as first described by Richardson et al. (1995). The results of using the PICO table and discussion with NMBU University Library have been used to create the best possible search strings (table 1). To optimise the search string the boolean operators “OR” and “AND” were used.

Table 1
An overview of strings used in Web of Science.

("novel" OR "alternative") feed ingredients* AND "aquaculture" AND "sustainability"
"norwegian" AND "aquaculture" AND "sustainability" AND "feed" AND (environmental effects* OR environmental impact*)

"marine invasive species" (effects* OR "ecological" OR “environmental sustainability” OR "biodiversity" OR ecosystem*)

(“pacific oyster” OR “magallana” OR “crassostrea”) AND (effect* OR impact*) AND ("invasive" OR "non-native") AND (“environmental sustainability” OR "biodiversity" OR "ecosystem*")

(“oyster" OR "mussel" OR “bivalve”) "feed” AND "aquaculture" ("salmon" OR "norway" OR "norwegian") AND (“environmental sustainability” OR "sustainable" OR "environmental") (effect* OR impact*)

("bivalve*" OR "oyster*" OR "mussel*") AND ("fish feed" OR "feed") AND (sustainable OR sustainability OR environment*)

("bivalve*" OR "oyster*" OR "mussel*") AND (sustainable OR sustainability OR environment*) AND "fish feed"

"production of feed" OR "feed production") AND "aquaculture" AND ("sustainability" OR "sustainable")

("feed production" OR "production of feed") AND (improving sustainability OR improved sustainability OR impact sustainability OR affect sustainability)

Conducting the systematic literature search

The literature search was conducted 22.01.23 using Web of Science. The search was completed by searching all possible fields of study and combining the strings using the boolean operator “OR”. No articles were excluded based on year, as articles about invasive species, oysters and sustainability were deemed to be interesting regardless of age. Articles were not excluded based on language, but as the search strings were in English there is a possibility that relevant articles in other languages were excluded.

The first search yielded **1016** results. To narrow the articles and ensure that the relevant articles were included, the following method was utilised. This method is also described in figure 3.

1. If it was uncertainty surrounding the articles relevancy after reading the headline, the abstract was read, and the articles were imported into EndNote (version 20, bld 16860). The number of articles imported to EndNote was **205**.
2. The duplicates were deleted with EndNotes’ function to do so, and the number of references were reduced to **154**.
3. About **3** articles were read within each of the themes: i) oyster impact on invaded areas, ii) invasive species management, iii) soy impact on sustainability, iv) fish meal impact on sustainability, v) reducing the impact of feed ingredients. The total number of

articles was **16**. All articles were published in a peer-reviewed scientific journal. The remaining 138 articles were discarded.

4. While reading the 16 articles, 56 additional articles were found in the reference lists which were read at different levels of completion and used in the literature review. Of these, **7** were included in the original search.
5. All in all, **72** articles were studied to complete the literature review, whereas 23 were part of the original search and 49 were found in the reference list of the original search articles.

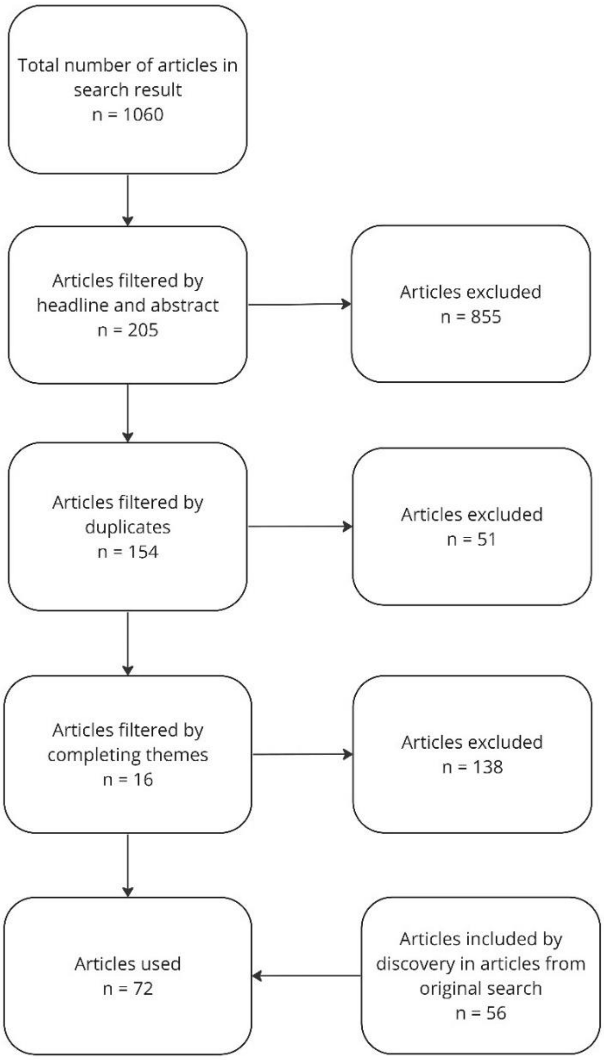

Figure 3 Overview of elimination process in article search.

Sometimes parallels are drawn between the blue mussel and the Pacific oyster if no studies on the Pacific oyster can be found. The blue mussel was chosen because it's niche overlaps with that of the Pacific oyster, it has been evaluated as a replacement for fish meal and is widely spread throughout the coast of Norway (Afrose et al., 2016; Bakken et al., 2021; Eschweiler & Christensen, 2011; Jönsson & Elwinger, 2009)

4.2 Interviews

Qualitative interviews rely on non-measurable data, commonly known as qualitative, or "soft" data, as opposed to quantitative, or "hard", data that can be measured. This type of data is typically gathered through open-ended questions that allow respondents to express their views and experiences in their own words, providing rich and nuanced insights that are not easily quantified (Miles & Huberman, 1994). The interviews were conducted in a semi-structured way, opening for the possibility to explore interesting topics that may come up outside of the intended questions as stated in Brinkmann (2014). This type of interview was included in the methodology of the thesis because it provides an overview of the participants' experiences, knowledge and opinions on the topic being investigated. To better understand the wants, needs and challenges in the market of feed production, an employee from each of the four largest salmon feed production companies in Norway were interviewed. Furthermore, Petter Bjørge from the oyster harvesting company Storm Østers AS was interviewed to understand the company’s pain points and largest drivers of cost.

Preparing the interviews

Prior to the interviews, the interview questions were added to a template. These questions were used as a guide, allowing both the interviewer and the participant to deviate from the questions if necessary. The template can be found in appendix 1. The participants from the feed companies were partly chosen by one of the supervisors of this thesis and partly by reaching out to the companies.

Managing the privacy of the interview participants

When doing research with people involved, there are ethical considerations to be made. Participants should not be harmed, informed consent should be obtained, participants' right to privacy should be respected, and no deception should be used (Bell et al., 2019). While all these are important to this thesis, it is particularly relevant to emphasise that the privacy of the participants have been ensured and that written consent was obtained. In January 2023 the NSD was informed of the interviews and approved them before they were conducted. Prior to the interview, all participants were sent a letter of consent by email which included their rights regarding privacy, participation and how their data would be stored. They signed and returned the consent form by email. As some of the participants from the feed production companies wanted to remain anonymous, all participants were anonymised. Petter Bjørge from Storm Østers AS wanted to be recognised in the thesis. The video with audio is kept on a password protected server at NMBU. The transcripts of the interview with the feed producers does not contain any identifiable information. All the data except from the transcribed data will be deleted when the thesis is concluded.

Execution of the interviews

The interviews were conducted on Teams (version 1.6.00.6754) and lasted between 30–60 minutes each in the days between 21.02.2023 and 02.03.2023. The interviews were initiated by me, introducing myself, the reason and purpose for the interview, emphasising the possibility of withdrawing from the process at any time, and again informing the participants of what would happen to the data they provided once the thesis was completed. The feed producers were shown the nutrient analysis provided by IVL Swedish Environmental Institute and prepared by Mathilda Nyquist, and a nutrient analysis provided by the Faculty of Biosciences at the Norwegian University of Life Sciences. These analyses can be found in appendix 2. The full amino acid profile and digestibility were not available at the time of the interviews and were therefore not included in the interviews.

Analysis of the interviews

The interview analysis was done based on the method in Braun and Clarke (2006) and followed this structure:

1. *Data immersion:* A considerable amount of time was spent both transcribing and reading through the transcripts while taking notes to ensure a familiarisation with the data.
2. *Generating codes:* Instead of generating initial codes, as suggested in Braun and Clarke (2006), each response was sorted under the associated question. Some of the questions were not in the initial guideline and were added to the analysis during this stage.
3. *Searching for themes:* Interesting and/ or recurring themes were identified to aid in the quantifying of the qualitative data.
4. *Reviewing themes:* It was confirmed that there was enough data for each theme to support them. Overlapping themes were merged.
5. *Defining themes:* It was clarified what the themes concerned and specified where needed.

6. A final report was produced, including a synthesis of all responses to each theme.

The information that is displayed in “6.2 Interviews” is based on the information that was collected during the interviews and shows the themes the interviews were divided into.

4.3 Nutrient analysis of dried oyster meal

Handling before analysis

The Pacific oysters used in the nutrient analysis was harvested by hand 5th of January 2023 from Ekholmsundet, 1690 Herføl, Norway. The oysters were taken out of the water, and within four hours they were opened and put on ice and transported to NMBU. At NMBU the meat was removed from the shell and freeze-dried. The freeze-dried oyster meal was then pulverised at a scale of 1 mm and stored at +3 degrees Celsius before being further analysed.

EPA+DHA provided by IVL

The EPA+DHA content of dried oyster meal was provided by IVL Swedish Environmental Research Institute as shown in table 4. These results should be regarded as representative EPA+DHA levels in Pacific oyster, but not necessarily as identical to the levels in the oyster product used for the digestibility trial at NMBU The remaining nutrient and amino acid profile was provided by The faculty of biosciences at The Norwegian University of Life Sciences, as respectively shown in table 4 and table 5. At IVL the oysters were shipped to Eurofins for analysis. Feed ingredients are compared on a dry matter basis as this makes it possible to compare them when they have a different water content on a wet weight basis. The method of analysis used in the Faculty of Biosciences was as stated in Tjernsbekk et al. (2017):

Analysis

The dry matter (DM), ash, crude protein (CP), total fat, and amino acids (AA) of the dried oyster meal were analysed. Additionally, the CP of freeze-dried faeces samples were analysed in order to calculate protein digestibility. The dry matter was determined by drying the samples at 103 °C, while ash was determined by combusting the samples at 550 °C for 10 hours. Nitrogen was analysed using a Kjeltec 1015 Digester at 420 °C and a Kjeltec Auto 2400/2600 (Foss Tecator AB, Höganäs, Sweden), and CP was determined as N x 6.25. Crude fat was determined by extraction using petroleum ether and acetone in an Accelerated Solvent Extractor (ASE 200) from Dionex (Sunnyvale, CA, USA). The content of total carbohydrates was calculated by difference: carbohydrates = *DM - (CP + crude fat + ash)*. Finally, the content of AA was analysed according to the European Commission Directive 98/64/EC (EC, 1998: cited in Tjernsbekk et al., 2017).

4.4 Digestibility measurement of dried oyster meal

To determine the apparent crude digestibility coefficient of the dried oyster meal, the dried oyster meal was mixed with standard ingredients including precooked corn starch, cellulose powder, soybean oil, fish meal, and a supplement of vitamins and minerals before being fed to mink (*Neovison vison*). Water was added to make a proper consistency. The dried oyster meal contributed with 50% of the protein in the feed mixture. The mink trial was carried out at Centre of Animal Research of the Norwegian University of Life Sciences in Ås, Norway (National permission number: 2012-15-2934-00394 in accordance with the institutional and national guidelines for the care and use of animals (NMAF, 1996, 2009)). The animals used in the study were adult male mink (*Neovison vison*) of the brown genotype. Mean body weight was 2.5 +/– 0.2 kg. Four healthy mink were fed the experimental diet with dried oyster meal. The animals were kept in individual cages equipped for controlled feeding and quantitative faecal collection, separating faeces and urine as described by Jørgensen and Hansen (1973). The experiment was conducted in a well-ventilated room with controlled temperature (18 ◦C) and lighting to adjust the day length to natural photoperiod. The experiment lasted for 7 days, of which the first three days were used for the adaptation of the mink to the feed and the following four days were used for the faecal collection. Feed allowance was 62–65 g dry matter (DM) per day corresponding to the daily requirement of metabolizable energy, i.e., of 600 kJ/ kg BW 0.75. Feed was given once daily, and feed intake and faecal production were registered once every day in the faecal collection period. Faeces from each animal were pooled over the four-day collection period and freeze-dried, grounded and sifted to remove hair.

The apparent total tract crude protein digestibility (ATTD) was calculated by use of the following equation: *ATTD (%) = ((crude protein consumed (g) crude protein in faeces (g))/ crude protein consumed (g)) x 100* (Tjernsbekk et al., 2017).

5. Literature review

5.1 What are the impacts of the invasion of the Pacific oyster on ecosystems and sustainability?

Table 2

An overview of impacts on ecosystems and sustainability from the invasion of the Pacific oyster.

General theme	Theme	Direction of effect	Impact on general theme	Area	Author
Biodiversity	Habitat heterogeneity	Increased	NI	Northern Wadden Sea, Germany	(Diederich et al., 2005)
		Increased	Depends on other factors	NI	(Padilla, 2010)
		Increased	Positive	NI	(Lotze, 2005)
	Competition with native species	Increased	NI	Bourgneuf Bay, France	(Cognie et al., 2006)
	Invasion on mudflat	NR	Positive	Lough Foyle and Lough Swilly, Ireland	(Green & Crowe, 2014)
	Invasion on mussel-bed	NR	Neutral/ negative		
	Survivability of blue mussels	Both	NI	Wadden Sea, Germany	(Buschbaum et al., 2016)
	Competition of quality sites (blue mussel)	Increased	Negative	NI	(Troost, 2010)
	Resilience against other invaders	Increased	Positive	NI	
	Cascading effects	Increased	Neutral/ negative	NI	
	Effect on native fauna	Increased	Positive	Southern Wadden Sea, Germany	(Markert et al., 2010) (Reise, 1998)
	NR	NR	Depending on habitat, density	Habitats similar to Europe	(Herbert et al., 2016)
	Predators' ability to feed	Decreased	Likely negative	NI	(Grabowski, 2004)
	New strains of virus and parasites	Increased	Negative	NI	(Ruesink et al., 2005)
GHG	CO_2/CH_4 emissions	Increased	Negative	Laboratory setting	(Green et al., 2012)
Socio- economic	Injuries to humans	Increased	Negative	The Netherlands	(Wijsman et al., 2008)
	Compete with commercial mussel production	Increased	Negative	The Netherlands	
	Reefs protecting shoreline	Increased	Positive	Galway bay, Ireland	(Hynes et al., 2022)
	New strains of virus and parasites	Increased	Negative	Different European sites	(Boxman, 2010)
	Gap between economies	Increased	Negative	Different sites	(Martínez-García et al., 2022)

NI: no info

NR: not relevant

According to The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IAS has been identified as one of the main drivers of biodiversity loss, which in turn poses a major threat to human well-being (IPBES; Pyšek et al., 2020). The effects of the invasion IAS are multiple and complex, and they should be viewed together to fully understand the impact an IAS may have on an ecosystem (Green et al., 2012). Generally, the impacts of IAS increase with their density (Sofaer et al., 2018).

The effects of the invading Pacific oyster, are both complex and multifaceted (Troost, 2010). In short, the Pacific oyster adds heterogeneity (variety in habitat type) which enhances biodiversity, but it may also eradicate other species in the same niche, which in turn can cause cascading ecosystem effects. The increase in biodiversity can happen because other species known to produce hard substrate, shelter and food to other species have mostly disappeared (Lotze, 2005: cited in Troost, 2010). Such species are flat oyster beds (*O. edulis*), blue mussel beds (*M. edulis*), reefs by a marine polychaete worm (*S. spinulosa*) and seagrass meadows. However, there is evidence linking the invasion of the Pacific oyster to potential change and decrease of native species and habitat (Cognie et al., 2006; Diederich et al., 2005; Green & Crowe, 2014). Additionally, the strength of the invasion is impacting the effects on biodiversity (Green & Crowe, 2014). Green and Crowe (2014) found that biodiversity increased when the Pacific oyster invaded mudflats, while having negative impacts when invading at higher cover in mussel-beds. In mudflats they increased biodiversity by providing hard substrate where there previously was none, which in turn created habitat for many species. The Pacific oyster may also bring socio-economic impacts, such as injuries that arise at beaches (Wijsman et al., 2008: cited in Herbert et al., 2016).

While oysters may increase the successful establishment of IAS originating from the same north-east Asian area, they may also aid the invaded area in becoming more resilient against other invaders as native biodiversity strengthens (Troost, 2010). The feeding efforts made by the Pacific oyster may change the occurrence of phytoplankton, which in turn may change the entire ecosystem due to limiting feed resources up through the food web. Seabirds might be affected this way, as the fish they are feeding on become less abundant, while seabirds that mainly feed on native bivalves might find less food if the oyster reefs expand. However, some other intertidal mussels might now be more readily available to foraging birds due to growing on the oyster reefs.

The ecological effects of the invading Pacific oyster vary substantially between European countries (Herbert et al., 2016; Markert et al., 2010; Reise, 1998; Troost, 2010). In some countries, the Pacific oyster seems to fill the niche left behind from the flat oyster, while in other countries, it competes with the blue mussel. While the Pacific oyster shares exactly the same habitat as very few other bivalves, it does share habitat with the blue mussel, increasing competition for high quality sites (Troost, 2010). Even though there have been reports of a decrease in the blue mussel populations at the same time as the Pacific oyster has invaded Northern Europe, this seems to be an effect of climate change rather than an effect of competition (Nehls et al., 2006). On the other hand, there has been reports of the Pacific oyster competing with commercial mussel production (Wijsman et al., 2008, cited in: Herbert et al., 2016).

The Pacific oyster alters the invaded ecosystems by building solid large three-dimensional reefs by recruiting new spat onto old or dead shells (Walles et al., 2016). This means that even after passing, the Pacific oyster may continue to alter the physical properties of an ecosystem due to its reef building properties (Gutiérrez et al., 2003; Padilla, 2010). Buschbaum et al. (2016) found that the Pacific oyster may act as an ecosystem engineer when invading spaces with the blue mussel. The blue mussels are often overgrown by barnacles, making it hard for them to feed, and in some situations it negatively affects growth and reproduction. Buschbaum et al. (2016) studied oyster reefs in the Wadden Sea outside Germany. They found that reefs built by the Pacific oyster may increase the survivability of the blue mussel because the reef may act as shelter against both barnacles and predators. However, food is less abundant in the lower layers of the reef, which results in the blue mussel experiencing a trade-off between being sheltered from predation and barnacles, experiencing a lower growth rate. The reef structure provides shelter from predators for multiple species, which in turn impacts predators' ability to feed, which may have cascading effects in the ecosystem (Grabowski, 2004; Grabowski et al., 2020). Additionally, the reef structures seem to raise and stabilize sediment surfaces over a longer time period than mussel beds, which may aid in preventing erosion in some intertidal flats (Commito et al., 2008; Reise, 2002). Prevention of erosion of the intertidal flats may protect the species in the intertidal zone against storm surges and ensure the continuation of recreational activities associated with the shoreline (Hynes et al., 2022).

Different strains of viruses have been documented at different production sites of the Pacific oyster. These are viruses that might transfer to humans, such as norovirus (Boxman, 2010). The Pacific oyster has brought new diseases and parasites that can infest and threaten native species (Ruesink et al., 2005). Furthermore, the production of shellfish may be threatened by climate change that can bring increased eutrophication that may lead to toxic algal blooms that can kill large quantities of shellfish or render them inedible due to toxins such as paralytic shellfish poisoning (PSP), lipophilic shellfish toxins (LSP) and amnesic shellfish poisoning (ASP) (Callaway et al., 2012; Stewart-Sinclair et al., 2020). Shellfish aquaculture is further threatened by climate change due to ocean acidification. During acidification there is a decline in ocean carbonate ions, and it has been observed that increased acidification leaves organisms producing calcium carbonate ($CaCO3$) struggling to maintain these structures (Cooley & Doney, 2009).

Even though the Pacific oyster does not contribute greatly to $CO2$ and $CH4$ emissions in itself, the sediment they are connected to may emit these gasses, and at an increasing level associated with an increased abundance of oysters (Green et al., 2012). When Green et al. (2012) tested this hypothesis on a mud-flat, they found that when the oysters were in high abundance, the emissions of $CO2$ were 13 times higher, and the emissions of $CH4$ were 6 times higher, than a mud-flat without the oyster. The research was done in a laboratory setting, requiring further investigation to be able to take the total release of greenhouse gasses into account in a carbon budget.

Regarding economic sustainability, Martínez-García et al. (2022) found that the introduction of the Pacific oyster seems to be correlated with a country's Gross Domestic Product per capita, suggesting that investment in infrastructure and research renders poorer countries more unable to explore the novel aquaculture species.

5.2 What are the chances of eradicating the Pacific oyster with management efforts?

According to Alves and Tidbury (2022) there is a tendency towards trying to eradicate IAS, while that often is not possible, especially not in open systems such as water (Booy et al., 2017; Sambrook et al., 2014). There is a correlation between the effort that is required to control the population and both the level of invasion and the capacity the invader has to spread (Ojaveer et al., 2015; Williams & Grosholz, 2008).

The impacts of IAS are often increased with their density, therefore it is important to evaluate management that can reduce density – termed “maintenance management” (Simberloff, 2021; Sofaer et al., 2018). According to Simberloff (2021) and Ojaveer et al. (2015), only a few marine IAS have been successfully eradicated due to having been detected early and management efforts were promptly engaged. In a study investigating the capability of Bahamas’ reefs to suppress the invasion of the Lionfish, Green et al. (2014) found that in the ecosystems where the spread and invasion of non-native species are controlled, there can be a beneficial effect on the ecosystem, increasing their resilience in the meeting with IAS. However, no marine IAS have been managed at low levels for a substantial amount of time (Simberloff, 2021). There is a lack of data and understanding of the interplay between key population drivers and IAS management. The decision on which management tools to use are often driven by this knowledge, and a lack of this knowledge may in turn have a negative impact on the effectiveness of the management option (Booy et al., 2017; Booy et al., 2020). In the research done by Giakoumi et al. (2019), raising public awareness and facilitating commercial use was deemed two of the most important management strategies. Commercial use of the IAS can encourage a self-sustained control or eradication of the IAS. However, if the IAS become an important source of income, communities might try to protect the IAS, demonstrating the importance of evaluating different factors when developing commercial management strategies (Nuñez et al., 2012). Raising public awareness is thought to positively impact the public acceptance of management interventions and encourage the public to aid in dispersion control (Giakoumi et al., 2019). However, according to Mortensen et al. (2019), the impact of trying to control the dispersion of the Pacific oyster may do more harm than good to the ecosystem if the harvesting technique is not chosen with great care.

There is evidence suggesting that it will be more or less ineffective to fully eradicate the Pacific oyster, as it may re-settle with the help of ocean currents and ships ballasts (Anglès d’Auriac et al., 2017; Wood et al., 2021). The re-settling will be further aided by increasing temperatures associated with climate change, as the reproductive success of the Pacific oyster greatly improves with increased temperatures (King et al., 2021). Thus, if the population is affected by external recruitment, the management is less effective as removal does not affect future recruitment in the area (Alves & Tidbury, 2022). To reduce recruitment of the Pacific oyster, farmed oyster aquaculture may increase their use of triploid individuals (infertile individuals) and cleansing ballast water. Additionally, climate change may increase recruitment through increasing flow of larvae in ocean currents and anthropogenic vectors (Anglès d’Auriac et al., 2017; King et al., 2021; Wood et al., 2021). According to the findings of Alves and Tidbury (2022) in an experimental trial, the increased recruitment of the Pacific oyster caused by climate change can be reduced by maintenance management, but can not be reversed. Furthermore, they found that populations that have high levels of recruitment are considerably impacted by maintenance management, both in the short and long term, but that increasing temperatures require an increase in maintenance. This means that when temperature rises, the Pacific oyster recruitment increases, and so does the need for maintenance management.

The negative effect IAS have on ecosystems has been followed up by the EU, who has made mitigation strategies known as the 8R - recognise, reduce, replace, reuse, recycle, recover/restore, remove and regulate (Rotter et al., 2020).

5.3 What are the challenges with today's salmon feed ingredients?

Table 3

Sustainability implications of salmon feed ingredients; soy and fish meal.

General theme	Type of ingredient	Theme	Impact on general theme	Author
Biodiversity	Soy	Less pressure on wild fish	Positive	(Couture et al., 2019)
	Multiple	Eutrophication	Negative	(Diana, 2009)
	Wild fish	Fish stock depletion	Negative	
Socio-economic	Soy	Antinutritional factors	Negative	(Booman et al., 2018) (Knudsen et al., 2007) (Van den Ingh et al., 1991)
	Soy	Limiting developing countries food production	Negative	(Darnton-Hill & Coyne, 1998; Solomons, 2000)
Land conversion	Soy	Deforestation	Negative	(Willaarts et al., 2011)
	Soy	NI	Negative	(Caro et al., 2018)
GHG/ resource use	Multiple	Cultivation	Negative	(Bohnes et al., 2022)
		Manufacture	Negative	
		Transport	Negligible	
	Multiple	Transport	Negative	(Pelletier & Tyedmers, 2007)
	Wild fish	Climate change	Negative	(Diana, 2009)
	Wild fish	Energy required to locate resource	Negative, but varies	(Pelletier & Tyedmers, 2007)
	Soy and fish meal	Soy compared to fish meal	Positive	(Pelletier & Tyedmers, 2007)
	Plants	Increased consumption of fertilizers, pesticides and water	Negative	(Cadillo-Benalcazar et al., 2020)
	Wild fish	2.7 times more energy demanding than plants	Negative	

Bohnes et al. (2022) stated that feed has a major impact in most of their measured impact categories. Both cultivation and manufacturing of the feed had major impacts, while transportation was negligible. This finding is cast doubt upon by Pelletier and Tyedmers (2007) which state that the impact of the feed can be significantly influenced by the mode and distance of transport of the ingredients. However, there are several factors contributing to the impact which could result in a scenario where a highly intensive production system that is run on hydrogen fuel can be less impactful than a less intensive system that is run on fossil fuel. Ziegler et al. (2013) also found that the emissions in aquaculture are largely attributed to feed use and especially composition through emissions of methane and nitrous oxide in agriculture.

Fish meal and fish oil have been known to affect both the immediate and distant environment through nutrient emissions, fish stock depletion and climate change (Diana, 2009). According to Diana (2009) the wild fish used in fish meal and fish oil is often made by pelagic fish species, which when disappearing, can contribute to a decline in larger predatory fish stocks. Fish from capture fisheries require a lot of material and fossil derived energy to locate the resource, a resource that can be very dispersed (Pelletier & Tyedmers, 2007). However, the energy and equipment requirement vary greatly between fisheries, mainly related to the stock health, species fished and technology used.

The pressure on wild fish stocks shows that there is a need for other sources of protein (Couture et al., 2019). As a result, almost all salmon feed has incorporated plant raw materials such as soy into their recipe (Aas et al., 2019). Even though it lessened the pressure on capture fisheries, it put enormous pressure on land (Couture et al., 2019). Studies show that the intensified soy use has increased the use and conversion of land (Caro et al., 2018; Willaarts et al., 2011). In addition to increased environmental pressure, antinutritional factors present in less refined legume products, such as soy, may induce detrimental effects when fed to salmon, such as decreased growth and nutrient utilization and intestinal inflammation (Booman et al., 2018; Heusala et al., 2020; Knudsen et al., 2007; Van den Ingh et al., 1991). To mitigate this issue, soy can be further processed into soybean concentrate. However, this further increases the environmental footprint of the ingredient due to requiring a larger input of soy and increased use of limited sources such as arable land, phosphorus and energy (Childers et al., 2011; Dalgaard et al., 2008). Pelletier and Tyedmers (2007) found that soy meal generated significantly lower impacts compared to fish meals. Furthermore, Bohnes et al. (2022) found that although soybean meal is a popular substitute for FM due to its high protein content, it also has one of the highest environmental impacts. The increased use of soy also limits the ability for developing countries to produce food for themselves (Solomons, 2000: cited in Couture et al., 2019; Darnton-Hill & Coyne, 1998: cited in Couture et al., 2019).

Cadillo-Benalcazar et al. (2020) found that even though plant-based ingredients generally require less labour, it also requires a greater consumption of fertilizers, pesticides and water than other feed ingredients. When replacing the marine ingredients in salmon feed with land-based ingredients, there will be an increase in demand for land, fertilizer and pesticides. However, marine-based feed and marine-insects feed are most energy demanding, being 2.7 times more energy demanding than plant-based feed. This finding is supported by Pelletier and Tyedmers (2007) which concluded their research paper with the statement that ingredients derived from animals had a greater negative impact than vegetable ingredients.

5.4 How can we reduce the impact of feed ingredients?

There has been an increased effort to develop and use feed ingredients that have a better fit to a circular and regenerative food system (Eroldoğan et al., 2022). Circular aquaculture and sustainability could be driven by reutilization of bioresources and increases the stress-resilience in fisheries and aquaculture (Lakre & Krishnani, 2022: cited in Eroldoğan et al., 2022; Alamerew et al., 2020). New ingredients should not only be considered in the view of environmental sustainability, but also sustainability in economic, social and governmental perspective (Alamerew et al., 2020). The most common part of sustainability that is considered in seafood sustainability, is environmental sustainability (Ziegler et al., 2013). Many factors influence the sustainability of a feed ingredient, including where the ingredient originates from, which ingredients are being used and the amount needed to produce a set amount of salmon (Cadillo-Benalcazar et al., 2020; Pelletier et al., 2009; Ytrestøyl et al., 2015).

Some feed ingredients are derived from by-products of fisheries for human consumption (Pelletier & Tyedmers, 2007). Pelletier and Tyedmers (2007) state that even though some by-products are not suitable for human consumption, the process of turning it into feed should still be examined for opportunities to improve. Furthermore, it should be put effort into keeping food that is suitable for human consumption in the market for humans, not using it for feed. Soy and many of the foraged fish species are suitable for human consumption and using it for direct human consumption would greatly improve the energy contained in the food chain.

Some of the most important enhancements that novel feed brings to aquaculture sustainability is related to their ability to use low-cost substrates, grow with minimal amounts of water and land (Cottrell et al., 2020). Eroldoğan et al. (2022) recognize novel feed ingredients, especially by-catch or discards from fisheries, as potential new value chains that can create jobs and contribute to an advanced economy. Furthermore, invertebrate IAS are recognised as potential natural resources due to their protein content. However, Cottrell et al. (2020) states that studies on fish meal or fish oil replacement have yielded inconclusive results regarding species growth and nutritional content, resulting in an unclear future for the scalability of new ingredients and to whether they can support sustainable feeding practices. On the other hand, according to Hertrampf and Piedad-Pascual (2003), mollusc meat is an excellent source of chemo-attractant properties for fish. Additionally, the farming of mussel species can reduce eutrophication (Kotta et al., 2020). Navarrete-Mier et al. (2010) found that oysters do not feed on waste from finfish aquaculture, making them unfit to form a circular system.

Feed production has the overwhelmingly largest impact on GHG emissions in farmed salmon (Ziegler et al., 2013). The blue mussel on the other hand, does not require feed input and has the lowest carbon footprint of all the farmed species (mackerel, herring, cod, saithe, haddock and salmon) tested by Ziegler et al. (2013). The authors note that the mussel farms have somewhat higher on-site emissions than salmon farms due to diesel burning boats used for harvesting and maintenance. Oftentimes the transport of seafood abroad constitutes less than 25% of the GHG emissions, but the blue mussel has very low edible yield, and transport is about 50% of the GHG emissions for the blue mussel. It is important to note that in this research the blue mussels were transported from Norway to Paris. Bohnes et al. (2022) suggests to tax old, less sustainable, technologies higher than new ones to promote more environmentally friendly technologies.

In some marine ecosystems with low salinity, the blue mussels are small, which can make them difficult to prepare into mussel meal (Eroldoğan et al., 2022). To address this challenge, black soldier fly larvae were fed a paste made of blue mussels which gave the larvae a favourable omega-3 profile. When the larvae were dried and turned into a meal, they were not only rich in omega 3, but also rich in protein.

The biotic energy consumed by a production species can also affect the sustainability of the product (Pelletier & Tyedmers, 2007). Biotic energy is energy that is mainly derived by plants in photosynthesis, where solar energy is converted into chemical energy. A food chain is composed of producers in the lower trophic levels and ends with some high energy demanding consumers. The energy is poorly preserved through each trophic level, meaning that harvesting from lower trophic levels would be beneficial in this regard.

Bohnes et al. (2022) suggest that convincing consumers to eat more seafood would decrease climate impacts, as aquaculture in general, and especially salmon production is much more climate friendly than beef production. Norwegian aquaculture production is anticipated to increase towards 2040, and so will the climate impact of feed. Reducing the world's demand for forage fish will greatly contribute to sustainability in the aquaculture sector, and many novel ingredients are able to offer rich sources of lipids and protein, the main nutrient that is derived from forage fish (Cottrell et al., 2020). The making of fish oil requires far more forage fish than the making of fish meal, meaning that the reduction of fish oil usage is most effectful. Additionally, the economic sustainability with the continuation of using forage fish in feed is affected by the fish stocks being highly variable, being closely linked to environmental events, and are sensitive to fishing pressure (Essington et al., 2015). All things considered, according to Cottrell et al. (2020), the broader environmental effects of using novel feed ingredients require further research, and there is a greater need for understanding the total effect on sustainability.

One of the most efficient ways to limit environmental impacts is to limit eutrophication by improving the feed conversion ratio (FCR) (Diana, 2009). The importance of improving the FCR is supported by Pelletier and Tyedmers (2007) which states that the FCR will have a considerable impact on the sustainability of the farming system, as it is a measure on how much of the nutrients are actually used by the fish. These nutrients have required a lot of energy and contributed to environmental impacts, and if they are not converted into fish, a great deal of them will pollute the water. Another way to limit eutrophication is to reduce disease and hence reduce mortality, as suggested by Bohnes et al. (2022).

According to Pelletier and Tyedmers (2007) substituting conventional salmon feed with organic salmon feed only produces a minor reduction in environmental impact of the feed production. They found that the largest reduction in feed production was associated with a decrease in animal derived ingredients. On the other hand, Maiolo et al. (2020) used the LCA method and found that poultry by-product meal and insect meal were the most sustainable options to substitute fish meal when compared with microalgae.

Cadillo-Benalcazar et al. (2020) questions the need for growth in the aquaculture if it does not increase food security, employment or the country's GDP, and suggest stopping the growth and rather focus on greening the current production.

6. Results

6.1 Nutrient analysis and digestibility

Nutrient analysis

The mean dry weight of the oyster was 10.9%, meaning that it consists of 89.1% water before freeze-drying. After drying, the oyster consisted of 93.9% dry matter. The composition of macronutrients; dry-matter, crude protein, ash, fat and EPA/DHA in the dried Pacific oyster meal, SPC and fish meal is shown in table 4. The EPA/DHA content of fish oil is also given.

Table 4

Macronutrient composition of dried Pacific oyster meal, soy protein concentrate and fish meal. All data are on a dry-matter basis.

	Dried Pacific Oyster meal (*Magallana gigas*)	**Soybean protein concentrate**	**Fish meal**
Source	As analysed at NMBU and IVL	Feedtables (n.d.b)	Feedtables (n.d.a)
Composition (g/kg)			
Crude protein	493	844	748
Ash	204	46	152
Fat	82	25	98
EPA (D 20:5) + DHA (C 22:6)	7.1[a]	0	11.2 (180-270[b])

[a] = data from IVL. The dry-matter content of this oyster product was 19.3% (for details, see section 4.3)

[b] = data on fish oil from Almås et al. (2020)

Amino acids

The essential amino acids and non-essential amino acids of dried Pacific oyster meal, SPC and fish meal is compared to the requirements of Atlantic salmon in table 5.

Table 5
An overview of the essential amino acid requirements of salmon, and the amino acid profile of dried Pacific oyster meal, soy protein concentrate, fish meal. All data are given on a dry-matter basis.

Nutrient	Atlantic salmon (*Salmo salar*) requirements	Dried Pacific oyster meal (*Magallana gigas*)	Soybean protein concentrate	Fish meal
Source	NRC (2011)	This study	(Feedtables, n.d.b)	(Feedtables, n.d.a)
Essential amino acids (%)				
Arginine	1.8	2.80	6.16	4.88
Histidine	0.8	1.02	2.20	1.78
Isoleucine	1.1	1.82	3.76	3.15
Leucine	1.5	2.81	6.55	5.37
Lysine	2.4	3.18	5.26	5.64
Methionine	0.7	0.78	11.8	2.08
Methionine + cysteine	1.1	1.33	2.60	2.71
Phenylalanine	0.9	1.19	4.26	2.91
Phenylalanine + tyrosine	1.8	1.77	7.20	5.21
Threonine	1.1	1.98	3.00	3.10
Tryptophan	0.3	NA	1.29	0.70
Valine	1.2	1.77	4.08	3.72
Non-essential amino acids (%)				
Cystine		0.54	1.42	0.63
Aspartic acid		3.75	9.69	6.80
Serine		2.02	3.37	2.91
Glutamic acid		5.95	15.30	9.49
Proline		1.97	4.51	2.79
Glycine		2.88	3.42	4.67
Alanine		1.24	3.62	4.63
Tyrosine		0.58	2.94	2.31

NA = not analysed

Figure 4 presents the profile of essential amino acids for the Pacific oyster using requirement estimates for essential amino acids in Atlantic salmon as the reference (NRC, 2011). Phenylalanine and tyrosine turned out to be the first limiting amino acids when salmon requirement was used as the reference, followed by methionine + cysteine, histidine, and lysine. The contents of non-essential amino acids were 50.6% of total amino acid and is found in **table 5**.

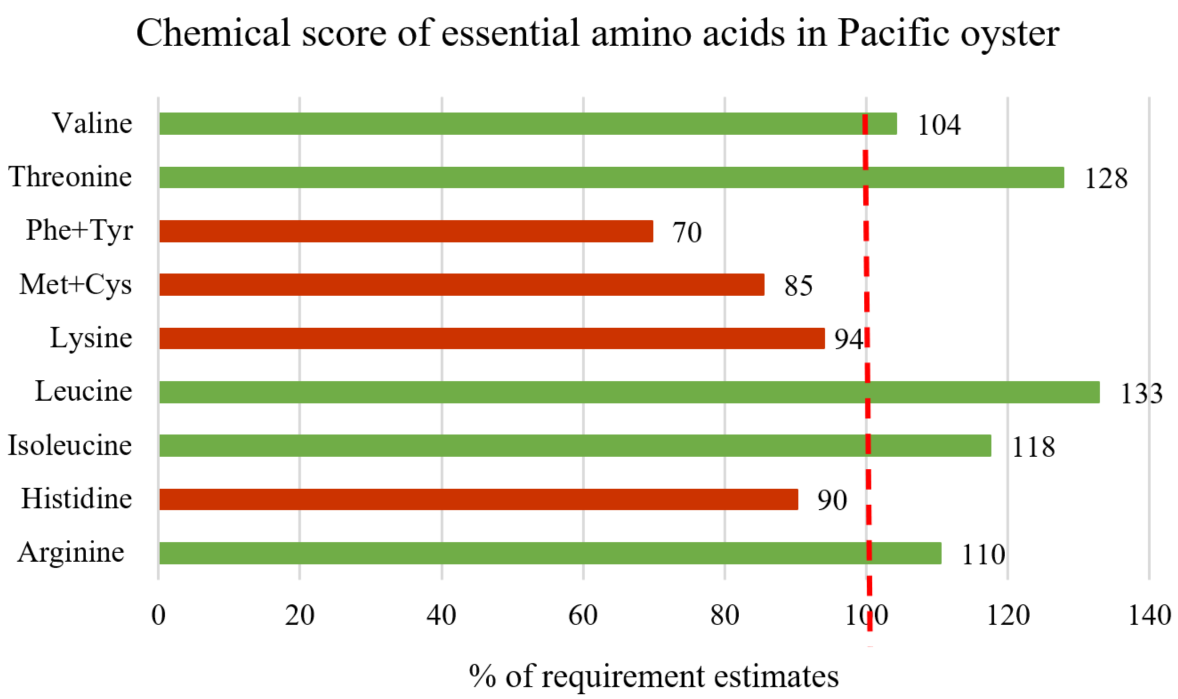

Figure 4 Chemical score for content of essential amino acids in the Pacific oyster as compared to requirement estimates.

Digestibility

The mean apparent digestibility for crude protein of dried oyster meal was measured to 79.5% with a standard deviation of 0.6. Comparable feed ingredients are shown in **table 6**, where fish meal has an 88-92% ADC and SPC has an ADC of 92.

Table 6

Apparent digestibility coefficient (ADC) for crude protein in the Pacific oyster, fish meal and soy protein concentrate.

	Pacific oyster	**Fish meal**	**Soybean protein concentrate**
Source	NMBU	(Ahlstrøm et al., 2004)	(Ahlstrøm et al., 2004)
ADC (%)	**79.5**	**88-92**[a]	**92**

[a] = Depending on the quality of the fish meal

6.2 Interviews

6.2.1 Feed producers

Nutrient profile

Protein or fat substitute

Feed producers disagreed as to whether the Pacific oyster would replace a protein fraction or a fat fraction in the feed. Some said that they considered it to be a protein source as it is mostly protein, although they normally want their protein sources to be between 60–70% protein. However, the same producers also said that they did not consider the Pacific oyster to be a typical bulk ingredient – which is the case for protein ingredients. Some said that it could be a substitute for both protein and fat, but that it would need a lot of "help" from other materials due to a lack of nutrients. One feed producer said that they don't want to replace anything, they want to grow.

Proteins

The amount of protein found in the dried Pacific oyster (46.3%) seems to vary between a little too low and just enough to be of interest to feed producers. The consensus was that the value would have increased if the protein had increased, and the carbohydrates had decreased. For comparison, fish meal is around 70% protein. This would imply a further processing of the oyster product.

The fact that the protein content of oysters can vary according to season or geographical location does not seem to bother feed manufacturers too much as they are used to variations in protein content, even though a given quantity needs to have a fairly homogeneous protein content. They do, however, adjust their price accordingly.

Fat

The feed producers did not show much interest in the fat content (7.7% dry weight (DW)), but some stated that it was the same as fish meal, which is good. Combined with the protein content, one feed producer stated that the Pacific oyster was an interesting but not optimal ingredient in salmon feed.

Fatty acids

Most feed producers were excited by the amount of DHA and EPA in the Pacific oyster and found it to be an interesting source of these omega-3 fatty acids. About 70% of the fatty acids are EPA and DHA, which means that it is about 7% EPA and DHA that adds value to the raw material. There is a high willingness to pay for EPA and DHA. However, one feed manufacturer had difficulty in understanding the amount of EPA and DHA but stated that they were interested in raw materials containing these fatty acids.

Amino acids

The amino acid profile that was shown to the feed producers was not complete, and one feed producer said it would be interesting to see a complete analysis, especially of the essential amino acids.

Ash

It was noted by most of the feed producers that the ash content was quite high and that this could be a challenge when used in salmon feed. One producer said that mechanically reducing the water content before drying the material could possibly reduce the ash content. One producer remarked that a lot of the ash content was made up of salt and that the salt content was too high. However, the producer did not consider the ash content to be too high in general, as fish meal tends to have about the same amount of ash (19% DW). They went on to say that the levels of minerals were interesting, and that vitamin C was unusual for marine ingredients.

Digestibility

One feed producer mentioned the importance of nutrient digestibility and said that they could accept digestibility as low as 80% but would prefer digestibility closer to 90%.

Commercial scale production

Volume

Two feed producers said that a few hundred tonnes per year would be sufficient for a novel feed ingredient, while the other two would require between 5,000 and 6,000 tonnes per year.

Silos

One of the reasons why feed companies are less interested in small quantities of feed ingredients is that small quantities do not optimise the use of their silos. Each ingredient is stored in its own silo unless it is very similar to another ingredient. One feed manufacturer said that the Pacific oyster could possibly be stored with the mussel. Another solution suggested by a feed manufacturer is to get help from the value chain, i.e., to find a buyer who is interested in using the novel feed ingredient to such an extent that they are willing to help finance the construction of a new silo. This can be the case if the customer is particularly interested in the nutritional profile, the sustainability of the ingredient or if it can be used in marketing.

Type of product

Feed producers typically divide their feed ingredients into two categories: bulk and additives. Some of the companies interviewed predicted that the Pacific oyster would be used as an additive, and probably not as a competitor to the bulk protein segment. To compete in the bulk category, the ingredient needs to be part of an industry with scale, a reliable product stream and a volume of several thousand tonnes. Additives often contain important vitamins, mineral blends, astaxanthin or colour. The value of these nutrients led one feed manufacturer to recognise the Pacific oyster as a potential natural source of EPA+DHA and zinc. Additionally, some feed ingredients can only be used in certain feeds or in one factory, making them more interesting in smaller quantities. To be interesting as a small-scale feed ingredient, the volume of Pacific oysters would need to be around 100–200 tonnes per year.

Price

It seemed difficult to answer what price they would be willing to pay to use the Pacific oyster in their feed. One feed producer said that they would first need to determine whether the oyster was a raw material used in bulk or in a smaller inclusion. Bulk material is often sold in large quantities and follows the world market price. Two respondents compared this with the price of fish meal (20–22 NOK/kg), and while one of them said that the price of the Pacific oyster would be considerably lower because fish meal has 70% protein and the Pacific oyster has 46.3% protein, the other respondent made a rough calculation: If we look at the value of today's fish meal, which is 70% protein and costs about 20 NOK per kg, and we multiply that by 46 [% protein, DW], we end up with a product worth 13 NOK per kg. The fat is about the same as in fish meal, 7–8%. This was a very rough calculation, and the digestibility will also affect the price. The respondent added that "the fact that there is a lot of carbohydrate probably makes the price even lower".

One feed producer suggested that the Pacific oyster would need help from customers or a market to start producing this raw material and a strong pull to reach scale. The larger the scale of oyster harvesting, the lower the unit price. Another feed producer predicted that the Pacific oyster would be valued for its protein content in addition to zinc and its value in organic feed. This respondent stated that the Pacific oyster could be used in niche products such as ecological feed. The amount of ecological feed they produced each year was between 20,000 and 30,000 tonnes per year.

Effect of sustainability on price

Feed producers were divided on how the sustainability profile of Pacific oysters would affect their price point. While two respondents said that there was currently no willingness to pay for sustainability, one respondent said that there was more willingness to pay now than a few years ago. This producer also said that there is a lot of competition in the area of sustainability. To be of interest to the feed manufacturer, the raw material needs "more than just sustainability", such as a solid business case with clear market benefits such as sustainability KPIs, quality benefits such as an interesting fatty acid profile, texture or colour [in the end product]. However, the nutritional profile will always be more important than sustainability. Some companies said that when evaluating new feed ingredients, it is a prerequisite that they are sustainably sourced, as they have seen their customers increase their GHG reduction targets.

Novel ingredients

Important aspects of novel ingredients

All feed producers agreed that the most important factor to consider when evaluating a potential new feed ingredient is the nutritional profile. However, availability, price and footprint were also considered important factors. One feed manufacturer also mentioned that they have a short delivery time to their customers and that they prefer the ingredient to have a shelf life of 6-8 months. Some producers said that digestibility was important because of its effect on salmon growth. The faster the salmon grows, the less time it needs to be kept in net pens, a practice associated with risk of disease, mortality and cost. In addition, one producer pointed out that the ingredient had to be legal to use and that it did not contain any undesirable substances.

Future ingredients

Most feed producers agreed that the future of feed ingredients is found in the sea. Some pointed out that Norway should seize the opportunity to harvest or cultivate raw materials from our long coastline. To achieve growth and sustainability in Norwegian salmon production, we must use the sea. One producer predicted that they would explore marine ingredients at different trophic levels, including mussels and oysters, perhaps from multitrophic aquaculture. There are a lot of initiatives to commercialise and optimise mussel farming and seaweed farming. Two feed producers stated that today's vegetable feed ingredients are being replaced by new feed ingredients and that they will not replace their marine ingredients in the near future as they source their marine ingredients from sustainably harvested fisheries. While the low trophic ingredients, such as Pacific oyster, blue mussel and seaweed are interesting, one feed producer pointed out that a lot of work needs to be done before any of these become viable feed ingredients. One feed producer said: "I hope we will use more circular ingredients. We need more sources of EPA and DHA. An EPA and DHA level of 3–5% is good".

Pacific oyster and sustainability

Impact on footprint

While we need to increase the use of marine resources and limit vegetable ingredients to increase sustainability, if the inclusion of the Pacific oyster is only a few hundred tonnes per year, the impact on the footprint is almost non-existent. If so, the footprint would have to be very, very small to have any effect. One feed producer said that they already do a lot of work with the raw materials they already use and try to reduce the footprint of those raw materials. They measure them against new raw materials and try to see if improving their current materials has a greater impact than introducing new materials. Another respondent said that we should use more circular feed ingredients.

A circular ingredient

Two of the feed producers agreed that we should use more circular feed ingredients, saying, "Anything you can harvest that you don't have to grow often makes sense. As long as you harvest sustainably, it is a resource that comes back every year without the need for fertiliser or pesticides.” However, they went on to say that in order to achieve sensible and sustainable production, you must have a value chain. The oyster must be harvested, processed and so on. The final sum must be positive, considering several aspects. Another respondent said that they found it interesting that they could contribute to limiting a problem as the Pacific oyster is an unwanted IAS.

Transport

One feed producer discussed the impact of locally sourced raw material on sustainability. They said that if the oysters are harvested by boat using fossil fuels, they will use a lot of energy to do so unless it is electric, or hydrogen powered. It depends very much on the efficiency of production as to whether the footprint of transporting oysters is greater than that of soy. If the product is locally sourced but still has a larger footprint, the fact that it's locally sourced doesn't add much value.

Opportunities and challenges

Challenges

Some feed producers said that the nutrient profile of Pacific oysters was one of their biggest challenges. The nutrient density is too low, only moderately interesting and does not automatically fit into their current salmon diets. The Pacific oyster should ideally be a little higher in fat and protein. In addition, the Pacific oyster has too much salt. It should be investigated whether it has an "x-factor" that can add value. "Price is a guaranteed challenge," said one feed producer.

Another challenge pointed out by several feed producers is the water content and that there would be a need for a lot of processing to remove it. One respondent said that they usually accept dry ingredients with a water content of 5–10%.

One feed producer questions the viability of building and scaling up an industry based on an IAS that you are trying to get rid of. While one respondent says that the Pacific oyster is probably manageable logistically, another says that it will probably be a challenge to get the volumes they want, and to process it without using too much energy.

Opportunities

One producer said that the Pacific oyster can potentially be a good source of natural zinc. Another feed producer said that the Pacific oyster has a lot of EPA and DHA as well as a relatively reasonable protein content and suggests harvesting the shell when it has the highest muscle content to get as high a protein content as possible. They also say that if the salmon likes the taste of the oyster, they can 'shower' the pellets with a mixture of the Pacific oyster to encourage the salmon to eat more.

6.2.2 Oyster harvesting company, Storm Østers AS

Effectivity

Every day Storm Østers AS can harvest about 500 kg oysters, meaning about 600 shells every hour. They are in the process of developing a new technology which they hope will increase their daily harvest to 4 tonnes. The technology was described as something between hand-harvesting and a vacuum. According to the oyster harvesting company's representative, Petter Bjørge, they will not vacuum the seabed, rather hand pick the oysters and use the vacuum to lift the shells into a container. They cannot vacuum the seabed because it is a national park, and they want to be as gentle as possible with the environment.

Harvesting permits

To be allowed to harvest in any area, Storm Østers AS must obtain a permit from Mattilsynet. To obtain the permit, they must submit tests for various viruses, such as noro and ecoli, as well as heavy metals and algae toxins. These tests cost around 65,000 NOK. The harvesting permit costs 12,000 NOK and lasts for one week. Due to the short period of the harvesting permit, they keep the oysters in containers in the water for about a month and harvest everything from the water within a week.

Harvesting strategy

Storm Østers chooses the places to harvest in their area according to the tides and weather conditions. According to Bjørge, they will never be able to completely empty an area because some of the oysters are "glued" to the rocks in the area. In addition, they do not want to empty an area because it ensures future recruitment. However, the main reason for not harvesting certain oysters today is the strict quality requirements for oysters sold as a delicacy.

Shell quality

Nowadays, the only Norwegian oysters that are sold on the Norwegian market are those that meet the standards required for oysters to be considered delicacies. According Bjørge, about 95–97% of the oysters in the water are too big, too oddly shaped, or not beautiful enough to be sold as a delicacy. These are oysters that can still be sold for human consumption, not as a delicacy, but as an ingredient in food.

Salmon feed

Entering the salmon feed market is interesting for Storm Østers AS due to the capital available in the market. However, the challenge with this market is that it is so big that even if the goal is to replace just 1% of the protein in a year's worth of salmon feed, you must supply 110,000 tonnes of raw material. Otherwise, the omega-3 content and the potentially interesting flavour profile of the Pacific oyster are identified as qualities that feed producers might find interesting.

Bjørge added that they believe the salmon industry is interested in positive publicity and that the Pacific oyster's strongest selling point might be its sustainability profile.

Cost drivers

One investment Storm Østers AS is working towards is the development of technology to increase the harvest. Another major investment will be the purchase of a boat that can take workers out to sea, which will also help increase harvesting. These technologies limit the need for manpower, which currently is a major cost driver in the business. Bjørge said that they hope to one day be able to develop technology that can harvest oysters autonomously. They have already made a drawing of a robot that "walks" on the seabed. However, Bjørge stressed that it is important that the robot does not leave footprints and damage the seabed, especially when operating in the national park. Bjørge said that the investment to make this robot a reality is being driven by their own investment, grants and loans. Due to the robot's ability to limit the use of manpower, he said that the long-term gain is greater as the alternative cost of manpower is a continuous and presumably increasing cost.

When asked whether this boat would be powered by fossil fuels or electricity, Bjørge said that they had been thinking about developing a boat that would run on electricity. They do not work far from shore, so it would be easy to return to shore to swap crew, deliver shells and recharge. While it is perfectly possible to build an electric boat, and that should be the goal, the technology does not seem to be readily available, and it will cost about 5 times as much as a fossil fuelled boat.

Bjørge followed up with information via SMS. He reported that the cost of one tonne of harvested oysters was 15,000 NOK. When asked whether new technology would reduce the cost, he answered that investments in new technology would keep the cost at approximately the same level. Furthermore, he reported that the oyster used in the analysis were harvested 5th of January 2023 from Ekholmsundet, 1690 Herføl, Norway.

7. Discussion

7.1 Will the use of Pacific oysters as a raw material in salmon feed positively impact sustainability?

Limiting the spread of the Pacific oyster and its impact on sustainability

One of the strongest arguments for creating a value chain for the Pacific oyster is that it will contribute to limiting the spread of an IAS. IAS can have detrimental effects on ecosystems and are recognised as one of the largest drivers of biodiversity loss and a major threat to human well-being (Brondizio et al., 2019; J. McNeely, 2001; Pyšek et al., 2020). Even though there have been reports of increased biodiversity in areas that have been invaded by the Pacific oyster due to the added heterogeneity, it can change food web interactions (Green & Crowe, 2014; Troost, 2010). Change in food web interactions can have cascading effects which likely will have unknown consequences in the ecosystem that can negatively impact both SDG no. 14 and 15. This is exemplified by Jackson et al. (2001), who states that a loss of a top predator, which in marine environments often are sea birds, can lead to an increased risk of eutrophication and introduction of new species in an area.

The Pacific oyster has overlapping niche with the blue mussel, but there are still no reports of the invasion of the Pacific oyster leading to a decrease of blue mussel stocks in Europe (Nehls et al., 2006; Troost, 2010)[3]. However, the Pacific oyster seems to occupy the best feeding sites, sometimes leading to decreased body weight for the native mussels (Waser et al., 2016). Additionally, the Pacific oyster is a host for other types of viruses and parasites, which can damage other molluscs, like the blue mussel (Ruesink et al., 2005). As the Pacific oyster have an overlapping niche and brings parasites and new virus strains, the shellfish industry could lose revenue and negatively impact the economic sustainability. As an example, the gross value of the blue mussel industry was 24,5 million NOK in 2021, an industry that is now potentially threatened by the invading Pacific oyster (Fiskeridirektoratet, n.d.). The likelihood of other industries being affected is likely to be greater if the Pacific oyster is not managed. In addition, the Pacific oyster may not be a reliable and consistent resource due to its susceptibility to viruses and parasites. In the 70s, there was a mass mortality of the oyster population in France due to a virus outbreak (Comps & Bonami, 1977: cited in Pernet et al., 2014). The risk of virus

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[3] A more recent reference article was not available, and this interaction may have changed since then. Oyster management work started in Norway in 2016, about 10 years after these results were published.

outbreaks is exacerbated by climate change as it can increase eutrophication, which can lead to increased occurrences of toxic algal blooms (O'Neil et al., 2012). Furthermore, this can create an unreliable resource and working environment, resulting in poor economic and social sustainability.

The current knowledge on the effects of the invasion in Norway is not strong enough to allow for the making of informed choices regarding the management of the Pacific oyster. Norway is bound by law to take precautionary measurements when dealing with an IAS where there are knowledge gaps, strengthening the argument for finding a suitable product to use it in (Naturmangfoldloven, 2023, § 9). At the same time, management methods that are not thoughtfully developed, might do more damage than good (Mortensen et al., 2019). Creating a value chain is a widely accepted management method, but it can lead the community that is economically invested in the IAS to protect it, rather than try to eradicate it (Giakoumi et al., 2019; Nuñez et al., 2012). This is supported by Bjørge from Storm Østers AS, who explains that they do not want to deplete an area in order to ensure future recruitment. One feed producer suggested harvesting the Pacific oyster at the time of year when protein content is highest, which may encourage oyster harvesting companies to delay harvesting to certain times of the year, thereby allowing for greater spread. On the other hand, the Pacific oyster is a marine IAS and is partly driven by external recruitment, so it is very unlikely that it can be completely removed (Simberloff, 2021).

Aiming for complete removal of the Pacific oyster might also be counterproductive if we want to ensure biodiversity, circling back to the fact that the Pacific oyster adds heterogeneity to the spaces it invades, allowing for shelter and habitat for a wider range of species. Due to a lack of management, it has come to induce major changes in a number of European estuaries (Mortensen et al., 2019; Troost, 2010). However, there is still much to learn about how to carefully harvest oysters in an efficient way, making sure the seabed is protected. According to Storm Østers AS, another of their large economic investments is to develop and build a robot that can harvest efficiently and gently. This is in line with the suggestion in the Millennium Ecosystem Assessment (2005), which is that technological advances that can increase yields without increasing environmental impacts can reduce the risk of biodiversity loss by reducing the need for land conversion at a time of growing food demand. This will also support SDG no. 12, ensuring responsible consumption and production. The optimal solution, if the goal is to ensure as high biodiversity as possible, might be to carefully harvest to keep the oyster from dominating certain areas, while not aiming to eradicate the oyster completely.

Mitigation of sustainability challenges of conventional salmon feed ingredients

The main challenges for fish meal and SPC are related to the unsustainable exploitation of fish stocks, the use of fossil fuels to locate fish stocks, land use change, increased use of fertilisers and water, and reduced food security in developing countries. These factors have negative impacts on the SDGs: zero hunger (no. 2), responsible consumption and production (no. 12), climate action (no. 13) life below water (no. 14) and life on land (no. 15). None of these are relevant to oyster harvesting, and replacing a portion of these ingredients with the Pacific oyster can have a positive impact on the environmental and social sustainability of salmon feed based on these categories. This is supported by Ziegler et al. (2013), who found that the blue mussel has the lowest carbon footprint of all the farmed species tested. The oyster can grow without added fertiliser or water, does not use arable land, and might even be aiding in cleaning the water. This is supported by a study by Kotta et al. (2020), stating that farming of mussel species can reduce eutrophication. Additionally, the biotic energy contained in a species can impact how sustainable it is (Pelletier & Tyedmers, 2007). The Pacific oyster occupy a low trophic level, resulting in them keeping a lot of the biotic energy the algae has derived from the sun.

There is a lack of knowledge about the effects of oysters on fish health and growth. While mollusc meat has shown promise as a chemo-attractant according to Hertrampf and Piedad-Pascual (2003), no studies have been done on the attractability of oysters to salmon. According to Cottrell et al. (2020) there has been inconclusive results on the effect of fish oil and fish meal replacements on fish growth and nutritional content. If the use of oysters leads to a decrease in FCR, the environmental impact may not be beneficial, as less nutrients may be retained in the fish and more leached into the water. This can lead to increased eutrophication. In this context, digestibility and attractability are important factors to consider. In this case, if the oyster negatively affects the nutrient uptake of the salmon, the resources used to produce the feed are not being used in the most optimal way and will lead to a negative impact on SDG 12: responsible consumption and production. As shown in table 6, the apparent digestibility of the Pacific oyster is 79.5%, which is a bit lower than fish meal (88–92%) and SPC (92%).

There is some debate as to whether reducing the distance that feed ingredients must be transported will have a positive impact on sustainability due to the volume of feed ingredients that have to be transported. However, if we can ensure sustainable harvesting of oysters using vessels that do not require fossil fuels, it is likely that the environmental impact of transportation will be reduced. This is supported by Ziegler et al. (2013), who found that mussel farms have slightly larger on-site emission than salmon farms due to fossil fuel driven harvesting vessels. According to Bjørge from Storm Østers AS, one of the biggest economic investments they are looking into is acquiring an electric vessel. However, the oyster shell is on average five times heavier than the oyster meat, so it is essential to create a value chain for the shell as well, in order to increase the value of the energy spent on transport (Fujiya, 1970).

While sustainability is increasingly important to consumers and governments, the consensus from the feed producers were that there was no, or very little, willingness to pay for sustainability. They go on to state that the feed ingredient needs to have a solid business case, and possibly quality benefits such as giving the salmon an interesting fatty acid profile, texture or colour. However, the nutrient profile will always be more important to the feed producers than sustainability. At the same time, the inclusion of the Pacific oyster would have to be relatively large, or the impact tiny, for it to have a significant impact on sustainability.

Oysters: food or feed?

The importance of moving towards a circular system is recognised by both the Norwegian government and the feed producers who have contributed to this thesis (Regjeringen, 2021). There has also been an increased effort in the research community to develop feed ingredients that fit into a circular system (Eroldoğan et al., 2022). Feed products that are suitable for human consumption should be kept in the market for humans to ensure efficiency in the use of arable land (de Boer & van Ittersum, 2018). Efficient use of arable land to produce food is important in protecting biodiversity and life on land (SDG 14), avoid emissions from land use change (SDG 13) and limit the use of fertiliser (SDG 12). According to Bjørge from Storm Østers AS, only 3–5% of wild oysters are of suitable size and shape for the human food market. While it is tempting to argue that 95–97% of wild oysters could be used to feed salmon, from a sustainability perspective, where the aim is to improve the amount of energy contained in the food chain, an argument can be made that many of these oysters are suitable for food. This is a line of reasoning supported by Pelletier and Tyedmers (2007), who states that keeping food that is suitable for humans in the market for human consumption will increase sustainability. Even if the oysters lack the visual qualities to enter the gourmet market, they could be a great resource for other food products and thereby helping to achieve SDG no. 2: zero hunger. This is in line with Storm Østers AS strategy of exploring other food markets for oysters where the visual qualities are less important.

The relevant hypothesis for this section is:
H_1: The use of the Pacific oyster in salmon feed will have a positive impact on the sustainability of the feed.

Due to the sheer number of environmental impacts from the production of SPC and fish meal, and the fact that the Pacific oyster does not need arable land, fertilizer or added water, it is likely that the use of Pacific oysters will have a positive impact on the sustainability of salmon feed. In other words, hypothesis H_1 is strengthened, but there are some uncertainties to the overall size of the effect. No comprehensive sustainability analysis, like an LCA, have been carried out on oyster harvesting, which makes it difficult to accurately compare the different impacts of the different feed ingredients. Furthermore, there is no knowledge of the on-site emissions of the Pacific oyster, how it compares to capture fisheries, or the energy requirements from processing the Pacific oyster.

7.2 Does the nutrient content and digestibility of the Pacific oyster relative to other commonly used feed raw material and the requirements of salmon make it an interesting raw material for feed producers?

Water

The unprocessed Pacific oyster consists of 89.1% water, according to the NMBU analysis. This is an indication of one of the biggest challenges in using the oyster in feed. The feed producers recognised the water content as a challenge and that the Pacific oyster would need a lot of processing before an acceptable water content could be achieved. One producer said that an acceptable water content was 5–10%. In the NMBU analysis, the oyster was freeze-dried, which is an energy-intensive process. The water content is a challenge for several reasons. It will require energy to remove it, which may reduce the sustainability of its use in feed. If the oyster is not being dried on site, it will also require “unnecessary” energy to transport, which essentially means transporting water that does not add value to the feed. Another potential challenge is the salt content of the water. According to one feed manufacturer, this is a challenge that could be solved by mechanically removing the water from the oyster. However, this is also a process that requires energy.

Protein

The crude protein content of the dried Pacific oyster meal was measured at 49%. Compared to fish meal (74% DM) and SPC (84% DM), this is a reduction of about 30–40%. However, fish meal and SPC are ingredients that have been refined to maximise their protein content. The Pacific oyster has only been dried, making it a less processed product. Processing is expensive, so the oyster is currently a cheaper product in terms of processing. However, both fish meal and SPC are produced in large quantities, and it is likely that they are less expensive to process per kg than oysters. If Pacific oyster production were to be scaled up, the protein content would reach 49% without requiring much processing, which could bring additional economic and environmental benefits. On the other hand, the protein content of the Pacific oyster seems to vary between a little low to just enough to interest the feed producers, and it is possible that the interest would be higher if the oyster could be refined in a way that increased the protein content. Additionally, the feed producers commented on the seasonal variation that might arise in raw materials such as the oyster, and said that they usually varied the price they were willing to pay according to the protein content. Linehan et al. (1999) found a seasonal variation of protein content in the Pacific oyster that ranged between 39.1–53.1% where the highest level was in August. The oysters used in the NMBU analysis were harvested in January, which may indicate that the protein content could be higher if harvested in the summer. At the same time, feed manufacturers reported that they need reliable access to feed ingredients, which means that the varying protein content would have to be taken into account.

Discrepancy between protein and amino acid content

There is a discrepancy between the amount of crude protein (49%) found in the test and the sum of amino acids (35.1%). As AA are the building blocks of proteins, AA and proteins should be present in equal amounts. One reason as to this difference is the potential inaccuracy in the method of estimating the protein content. The method utilised in this analysis, is called the *Kjeldahl procedure,* measuring nitrogen content of the sample and times it with the constant 6.25 (Chang & Zhang, 2017). The Kjeldahl procedure has received some critique for inaccurately measuring protein (Miller et al., 2007). Another reason for a discrepancy between the amount of crude protein and the amount of AA is that there could be other nitrogen sources than amino acids in the oyster meat. It is likely that a portion of that is ammonia, as oysters are known to excrete this compound (Mara et al., 2021). This means that there is probably less protein in the oyster than reported. However, as the Kjeldahl N method is widely accepted and used, the same uncertainty will be present in several reports on protein in other feed ingredients. At the same time, if there are other sources of nitrogen in the oyster, it may impact the apparent digestibility coefficient. It is likely that the protein digestibility is higher than what is reported in this analysis (79.5%). Future research on this topic should include analysis of amino acid digestibility to obtain a more accurate digestibility figure.

Digestibility

Digestibility is important for optimal growth of salmon as it impacts the feed conversion ratio (Liu & Selle, 2015). If not properly managed, nutrients that have been both economically and environmentally costly to produce can leach into the water, causing additional losses to both the economy and the environment (Hillestad et al., 1999). Feed producers said that digestibility was important due to its effect on salmon growth. Higher digestibility resulted in faster salmon growth and less time spent in net pens, a practice associated with risk of disease, mortality and cost. According to Diana (2009), one of the most efficient ways to limit eutrophication is by improving the FCR. The mean apparent digestibility measured in mink for the protein content in the Pacific oyster was 79.5%. This means that 21.5% of the proteins in the Pacific oyster will not be retained in the animal. It is important to note that the digestibility is measured using mink, and that there might be differences between the species. The correlation between digestibility in mink and salmon seems to be influenced by the type of ingredient, as the results of Mundheim (2010) showed a varying degree of correlation. However, the differences were small and it was concluded with that the digestibility measured in mink is highly correlated with that found in salmon, a finding supported by Takeda and Watanabe (1990). According to one feed producer, they could accept a digestibility as low as 80%, but preferred closer to 90%. The ADC for protein ingredients usually employed in Norway in 1999 was 87%. The digestibility of the Pacific oyster is acceptable, but not outstanding. The other ingredients, SPC and fish meal, have a generally higher digestibility, making it hard for the Pacific oyster to compete on this aspect. However, as previously discussed, there is reason to believe that the protein digestibility is higher than reported, but this requires further research.

Amino acids

Of the amino acids measured, the EAAs represented 49.4% of the total amino acids. As seen in figure 4, phenylalanine and tyrosine are the limiting EAAs with a chemical score of 70% of requirement estimates. This means that it is phenylalanine and tyrosine that will limit the growth if the Pacific oyster was the only protein ingredient in the feed, based on the requirement that exists of EAA in salmon today. Deficiencies in phenylalanine have been shown to decrease feed utilisation, decrease growth, and reduce antioxidant performance in fish (Borlongan, 1992; Zehra & Khan, 2014). The other limiting EEAs in the Pacific oyster are methionine + cystine (85%), histidine (90%) and lysine (94%). To ensure optimal digestion, the EAAs should be balanced with the different feed ingredients (Kousoulaki et al., 2021). This underscores the need for other feed ingredients that can supply the limiting EAA if the Pacific oyster was to be used in salmon feed. Although the feed manufacturers were not shown the AA profile as it was not available at the time of the interviews, one of them predicted that the Pacific oyster would need to be combined with other feed ingredients to make a complete feed.

Fat

The fat content of the Pacific oyster was measured at 8.2%. This was considered by some feed manufacturers to be an acceptable level. It is approximately the same as in fish meal (7.4%). Seen in combination with the protein content, the Pacific oyster was generally viewed as an interesting, but not optimal, raw material.

Fatty acids

The amount of EPA+DHA in the Pacific oyster was measured at 0.71%. EPA and DHA are highly sought after in the feed market and there is a high willingness to pay for them. The Pacific oyster was recognised as an interesting source of omega-3 by the feed producers. They said that they thought an EPA+DHA level of 3-5% was good. However, the IVL analysis is based on a different batch of oysters, with a dry matter content of 19.3% (see table 4). The oyster analysed by NMBU had a mean dry matter content of 10.9%, meaning that it is likely that there is a lower content of EPA+DHA in the oysters analysed at NMBU. This might be due to the oyster batches being harvested at different seasons or other variations in methods (Linehan et al., 1999).

Ash

Most of the feed producers said that the ash content was quite high at 20% DW and argued that this could be a challenge if used in salmon feed. On the other hand, one feed producer said that it was unproblematic as fish meal usually has the same ash content. This is supported by the nutrient analysis in the results, where the fish meal tested had 20.4% ash. Furthermore, the zinc and vitamin C content were deemed to be interesting according to the feed producers, possibly being an interesting alternative to use in organic feed.

Comparing dried oyster meal with SPC, fish meal and salmon requirements

NRC (2011) as a source

The salmon requirements used in the present work are mostly based on the NRC (2011) recommendations. The NRC (2011) reports these requirements as based on highly purified ingredients that represent close to 100% bioavailability. As shown by the results, SPC, fish meal and oyster meal all have a bioavailability around 80-90% (92%, 88-92% and 79.5% respectively). As a result, the requirements are somewhat modest compared to the actual amount of nutrients that needs to be added through the diet to ensure proper nutrition. While the NRC (2011) is one of the most cited literature on fish nutrition, the information is becoming old and some of it might be outdated. The knowledge of fish nutrition, and especially the requirements are continually developing, as stated by Liu et al. (2022). In addition, the change in diet composition from marine to plan-based has increased the content of alien compounds, such as plant antinutrients, which may affect nutrient utilisation, and thereby requirement (Krogdahl et al., 2010). According to Vera et al. (2020) the nutrient requirements that is found in the NRC (2011) should in many cases be increased. Additionally, nutrient requirements for salmon are not constant. They change with fish size, growth stage and environmental conditions (NRC, 1993). This means that the information that is stated in the NRC (2011) might already be outdated and that feed formulators use other, updated knowledge.

Different qualities of fish meal

While the nutrient composition of fish meal used in this thesis is within normal range, it should be noted that there are many different qualities of fish meal. Pike and Jackson (2010) show that there are a lot of variations in the fatty acids found in fish oil, a finding supported by Almås et al. (2020). Therefore, the results based on fish meal should be treated with some caution, as different types of fish meal are likely to yield different results.

The relevant hypothesis for this section is:

H_2: The nutrient content and digestibility of the Pacific oyster makes it an interesting raw material for feed producers when compared with fish meal, SPC, and the nutritional requirements of salmon.

The nutrient composition and digestibility make the Pacific oyster an interesting raw material, and the hypothesis H_2, is strengthened. However, this result comes with great uncertainties. The Pacific oyster has an EPA+DHA profile (0.71% DM) that makes it an interesting ingredient for the feed producers. However, the EPA+DHA profile is based on another batch of Pacific oysters than the analysis done at NMBU. The crude protein digestibility (79.5%) is barely within acceptability, but not outstanding. However, the digestibility is probably higher than reported, and it was not shown to the feed producers. The protein content (49.3% DM) varied from being a little too low, to barely interesting, according to the feed producers. However, due to uncertainties stemming from the methods protein was measured, it is possible that the protein content is even lower. Additionally, multiple feed producers responded that the nutrient density in the Pacific oyster is too low, and that it could potentially be used in ecological feed.

7.3 Is the current price of Pacific oyster in line with the price feed producers are willing to pay for them?

Cost per tonne oyster versus other feed ingredients

In figure 5, there is a summary of the cost of one tonne whole oysters, oyster meat, dried oyster meal, SPC and fish meal, given in 1,000 NOK per tonne. Dried oyster meal is by far the most expensive, at 825,688 NOK per tonne, and compares unfavourably to SPC at 9,000 NOK per tonne and fish meal at 17,725 NOK per tonne. This means that dried oyster meal is about 47 times more expensive per tonne than fish meal, and 92 times more expensive per tonne than SPC. This was also predicted by the feed producers, who said that price was guaranteed to be a challenge. The cost of dried oyster meal is without processing, which means that the actual cost of dried oyster meal is likely to be even higher. See appendix 3 for calculations.

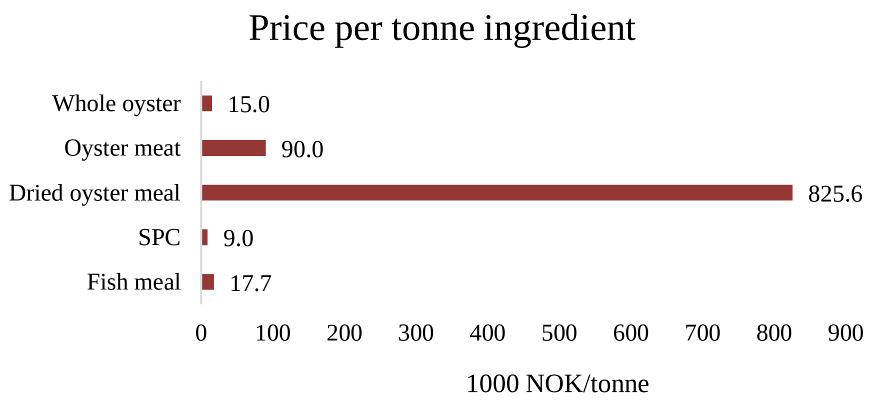

Figure 5: An overview of the price per tonne ingredient.

Time needed to meet minimum requirement of feed producers

In order to meet the minimum annual raw material requirement of 200 tonnes set by the feed producers, Storm Østers AS needs to harvest for 52 years with its current technology (table 7). With their new technology and the predicted increase in catch rates, they will need to harvest for 7.5 years. In other words, even with their new technology, they will not be able to achieve a large enough catch annually to meet the minimum needs of feed producers. In fact, their yearly catch with new technology of 1460 tonnes whole oysters, will only yield 26.5 tonnes dried oyster meal.

Table 7

An overview of the amount and time needed to obtain the annual requirement of 200 tonnes dried oyster meal.

Amount (number of whole oysters)	91,743,119
Years (current technology)	52 years
Years (predicted technology)	7.5 years

This result comes with considerable uncertainty. It was assumed 8 hour working day 365 days a year with current technology and 24/7/365 working days with the new technology. This is likely to be an optimistic assumption, meaning that the actual number of oysters harvested per year is likely to be lower for both current and new technology. In addition, the oysters harvested at the rate reported by Bjørge at Storm Østers AS are oysters destined for the gourmet market. However, if the end product is feed, the oysters may be significantly larger than the two-year-old oysters used here as a baseline. This means that the number of oysters that need to be harvested to meet the demand of feed producers may be lower. See appendix 4 for calculations.

Value of one tonne protein, EPA/DHA from dried oyster meal when compared with fish meal, SPC and fish oil

To find the value of protein and EPA/DHA content in dried oyster meal, it has been compared to the nutrient content and current price for fish meal, SPC and fish oil. The findings are summarized in table 8. The calculations can be found in appendix 5.

Table 8
An overview of the value of one tonne dried oyster meal when compared to the current price (NOK/ tonne) and nutrient content (%) of fish meal, SPC and fish oil.

	Value NOK/tonne dried oyster meal	**Current price** NOK/tonne	**Nutrient content** %
Protein			
Fish meal	11,683	17,725.75[a]	74.8[b]
SPC	5 257	9,000.00[c]	84.4
EPA/DHA			
Fish meal	11,237	17,725.75[a]	1.12[b]
Fish oil	714–476	18,110.33[d]	18–27[c]

Data from: [a] IndexMundi (2023), [b] Feedtables (n.d.a), [c] Almås et al. (2020), [d] Statista (2023).

When compared to the current price of 17,725 NOK/tonne and protein content (74%) of fish meal, one tonne dried oyster meal is worth 11,683 NOK/ tonne. When compared to the current price of 9,000 NOK/tonne and protein content (84%) of SPC, one tonne dried oyster meal worth 5,257 NOK/ tonne.

When compared to the current price of 17,725 NOK/tonne and EPA/DHA content (0.84%) of fish meal, one tonne dried oyster meal is worth 11,237 NOK/ tonne. When compared to the current price of 18,110 NOK/tonne and EPA/DHA content (18–27%) of fish oil, one tonne dried oyster meal is worth 714–476 NOK/ tonne.

In other words, the highest price Storm Østers AS should take for their feed ingredient is around 12,000 NOK/ tonne dried oyster meal. At present, their price per tonne dried oyster meal is 825,688 NOK. It is important to bear in mind that there are a number of other factors that can have an impact on price. The digestibility, the need for processing and the mode of transport are examples of factors that can influence the price of an ingredient. At the same time, it is somewhat inaccurate to compare the protein and EPA+DHA content of Pacific oysters with ingredients that have been refined to maximise these nutrients.

A feed for the future?

Almås et al. (2020) recognise that protein sources costing less than 50 NOK per kg are ideal, but they recognise protein raw materials costing 50–150 NOK per kg as feasible to use in 2050. Even though this is a steep increase compared to today's protein prices, Storm Østers AS will have to significantly scale up to be able to achieve this price reduction and to be able to harvest an amount that satisfies the feed producers. The feed producers said that there is currently no willingness to pay for sustainability, one of the largest selling points according to Bjørge at

Storm Østers AS. However, this might change in the future, and it may also be mandatory for feed ingredients to have a stronger sustainability profile than they have today.

Additional costs

There are additional processing costs if a buyer is only interested in the meat of the oyster. Ideally, the buyer would want the whole oyster. Otherwise, the oyster shell could be sold as a resource to other buyers, but if there is no interest in a potentially large amount of shell, the shells could end up being both an economic and an environmental cost. In addition, feed producers state that novel feed ingredients often require the construction of new silos for storage. As this is an additional cost on top of the cost of the Pacific oyster as an ingredient, feed companies emphasise the need for the Pacific oyster to be included in a value chain. A buyer who is willing to pay extra to include Pacific oysters in their feed may also be willing to pay for the construction of a silo. The feed producers also commented on the carbohydrate content, stating that it was likely to reduce the price even further.

The relevant hypothesis for this section is:
H_3: The price of the Pacific oyster makes it economically viable to use in salmon feed.

As the dried Pacific oyster meal will cost 825,688 NOK per tonne, it will not be economically viable to use in salmon feed, when other common feed ingredients are priced from 9,000 to 17,000 NOK per tonne. The hypothesis, H_3, is rejected. At the same time, Storm Østers AS will not be able to meet the lowest annual requirement of the feed producers. However, there may be a future where the price of raw materials has increased, there are stricter laws regarding sustainability, and the Pacific oyster is harvested on a larger scale with lower costs, where it is economically viable to use it.

7.4 Can the use of Pacific oysters in salmon feed be profitable on a larger scale in terms of cost savings?

Economic valuation of ecosystem services and the creation of self-sustaining management

There is missing knowledge about the complete economic value of Norwegian marine ecosystems. In line with the suggestions of the TEEB (2010) framework, an economic evaluation could act as an argument for stakeholders in creating a value chain for the Pacific oyster, thus potentially limiting further habitat change and biodiversity loss attributed to the invasion of the Pacific oyster. As previously mentioned, there is no clear knowledge about the impact of the Pacific oyster on biodiversity and ecosystem services, but to err on the side of caution includes taking precautionary action and limiting the spread of the oyster (Millennium Ecosystem Assessment, 2005; TEEB, 2010; Troost, 2010). While Norway's government has prohibited the cultivation of Pacific oysters to limit the spread and has started the work of assessing the potential for large-scale spread of the Pacific oyster, there is a somewhat missing governmental action in creating a value chain with the harvested oyster (Forskrift om akvakultur, 2023; Miljødirektoratet, 2016). According to Millennium Ecosystem Assessment (2005), there is often a lack of political will to make decisions about the management of ecosystem services, even when a monetary value is attached to them. Bardalen et al. (2020) suggest that there needs to be an additional pillar to sustainability: “governance sustainability”, which refers to the institutions that enforce sustainability measures. Even if the Norwegian government is ready to take action against the invasion of the Pacific oyster, there is a lack of knowledge about the potential of the Pacific oyster to spread (Miljødirektoratet, 2016). However, the government's action plan for the Pacific oyster invasion in Norway does not mention the potential economic costs of a large-scale invasion. This may be due to a lack of clear knowledge about the impacts of the invasion and a lack of clear economic valuation of some marine ecosystem services. If the Pacific oyster is included in a value chain, for example in salmon feed, the management of IAS could be self-sustaining and provide an incentive for conservation. However, there is a challenge in trying to supply a market that is virtually never satiated with an IAS, namely that there will be a greater incentive to conserve to ensure larger populations.

Substituting conventional feed ingredients with sustainable alternatives and the effect on ecosystem services

If the Pacific oyster is implemented as a raw material in salmon feed it can lead to a reduction in the use of soy and wild fish. The use of both soy and fish meal as feed resources can reduce the ability of producing countries to feed themselves, which is seen as a provisioning service (Millennium Ecosystem Assessment, 2005; TEEB, 2010; Troell et al., 2014). One way of capturing value in regard to the challenges with the cultivation of soy and capture fisheries, is through the creation of new market opportunities with other raw materials (Millennium Ecosystem Assessment, 2005; TEEB, 2010). In addition, demonstrating the value of the ecosystems that are displaced by soy production and the importance of healthy fish stocks on total ecosystem function can lead consumers to make different choices and decision-makers to set different priorities. While aquaculture has increased the global per capita fish supply, they are more or less absent in the areas where they are needed the most, such as Sub-Saharan Africa (Beveridge et al., 2013). The salmon industry often markets itself as working to produce food for a growing human population, but by relying on feed based on captured fish and soy, it is currently taking food from the poor to feed the rich (Beveridge et al., 2013; Lerøy, n.d.; SalMar, n.d.; Troell et al., 2014).

However, there is not necessarily a 1:1 relationship between the reduction in the use of soy and wild fish by Norwegian salmon farmers and the reduction in global consumption of these commodities. This can be exemplified by the abating of carbon emissions, where the reduction in emissions in countries that abate emissions is offset by an increase in emissions in countries that do not abate emissions, an effect known as "carbon leakage" (Paroussos et al., 2015). In other words, if Norwegian salmon farmers decrease their dependency on soy and wild fish, other buyers might be able to use those commodities due to a decrease in price and increase in availability, resulting in a scenario where the emissions are greater than at present. In addition, one feed producer stated that their company was not looking to replace any ingredients, but rather to increase their current levels to allow for growth. In this case, novel feed ingredients will allow the salmon farming industry to grow and may help to offset increased reliance on unsustainable feed ingredients but will not help to decrease the current use of these ingredients. Several feed producers said that they were looking to increase their use of marine ingredients, and limit their use of vegetable ingredients. Cottrell et al. (2020) state that the sustainability of aquaculture will be greatly enhanced if there is a reduction in the global demand for wild fish, a process that the Pacific oyster will not contribute to if feed producers are not looking to replace ingredients. Further, Norwegian salmon farmers claim to use “deforestation free soy”, but multiple studies are questioning the effectiveness of several of the certification systems and claim that there always will be leakage in such scenarios (Boucher & Elias, 2013; Hinkes & Peter, 2020; ilaks, 2022; Skretting, n.d.; zu Ermgassen et al., 2020). However, there is evidence suggesting that efforts to reduce emissions linked to soy production are net positive, even though there is some leakage (Villoria et al., 2022).

The Pacific oyster and ecosystem services

The Pacific oyster can add economic value to Norwegian marine ecosystems by contributing positively to ecosystem services or adding new ones. The Pacific oyster can contribute to provisioning services in the invaded areas by being a source of food or feed. In addition, it adds several regulating services such as eutrophication control by filtering the water and natural hazard regulation by building reefs that can act as protection against large waves (Hynes et al., 2022; Rice, 2001). Grabowski et al. (2012) estimated the economic value of the ecosystem services provided by oyster reefs to be between $5,500 and $99,000 per hectare annually, harvesting not included. They mention ecosystem services like water quality improvement, seashore stabilisation, carbon burial, habitat for fish, invertebrates and other fauna, diversification of landscape and oyster production. However, the Pacific oyster has a negative impact on disease regulation as it is a carrier of norovirus (Baker et al., 2011; Rupnik et al., 2021). It also has many negative impacts on cultural services, as the hard and sharp edges of the Pacific oyster may discourage people from visiting areas where it is present, contributing to reduced recreational value and ecotourism (Laugen et al., 2015). In addition, the Pacific oyster may negatively impact the supporting services of invaded ecosystems. By helping to upcycle nutrients captured by algae and other microorganisms, it would theoretically make nutrients available to species at higher trophic levels. However, the challenge is that in many of the ecosystems it invades, the nutrients it accumulates are not available to other species (Troost, 2010). Research suggests that the Pacific oyster is an unavailable feed source for most seabirds. It is important to note that the effects of the Pacific oyster on the invaded ecosystems are many and complex, and there is a need for complete evaluation of negative and positive impacts to manage the oyster invasion correctly.

Research suggests that invasion of the Pacific oyster can have negative implications on biodiversity, which is deemed to be one of the largest threats against human well-being (Brondizio et al., 2019; Green & Crowe, 2014; Pyšek et al., 2020). A decrease in biodiversity can impair the ecosystem resilience, which can lead to a cascade of negative effects in the ecosystem and severely limit the ecosystems ability to contribute providing its services (Côté & Darling, 2010; Folke et al., 2004; Oliver et al., 2015; Solomons, 2000). Management efforts through the creation of a value chain can provide economic incentives for conservation, allowing Norwegian marine ecosystems to gain some positive contribution to their ecosystem services while at the same time limiting the Pacific oyster's ability to outcompete native species, spread viruses and be a negative impact on cultural services.

Including externalities in the economic evaluation of feed ingredients

TEEB suggests that in demonstrating the value of ecosystem services, both the costs and benefits of conserving and restoring ecosystem services should be considered. The price of the Pacific oyster includes some of the value of the ecosystem services provided by the ecosystem from which it is harvested. Storm Østers AS limits the negative externalities from oyster production by carefully harvesting and planning to develop efficient harvesting technology in a sustainable way. Sustainable practices are expensive and add to the cost of Pacific oysters as a feed ingredient. However, as the value of the ecosystem services provided by the areas from which the Pacific oyster is harvested is not fully known, it is likely that the price does not reflect the total value of all ecosystem services that are protected by harvesting. At the same time, fish stocks are overfished, rainforests are converted to cropland, biodiversity is reduced and emissions increase. These are all externalities with economic impacts that are not reflected in the price of SPC and fish meal (Willett et al., 2019, cited in: Eyhorn et al., 2019). If the economic impact of the loss of ecosystem services using SPC and fish meal in feed was included in their market price, it is likely that the Pacific oyster would have a better chance of competing on price.

The importance of acting in line with the precautionary principle

According to TEEB (2010), decision-makers can be motivated to make precautionary decisions when provided with an economic value of the decision. However, Norway is legally obliged to act according to the precautionary principle when there is lack of knowledge about the effects of an IAS. The ecological effects of the invasive Pacific oyster vary considerably between European countries, and there is little knowledge mainly related to the Norwegian coast (Herbert et al., 2016; Markert et al., 2010; Reise, 1998; Troost, 2010). As suggested by Akins et al. (2019), the precautionary principle could be divided into socio-cultural, environmental and economic, and should be used when there is a threat to any of the three aspects. This is in line with the idea of “the three pillars of sustainability” – a framework to ensure that sustainability is done thoroughly with both the present and the future in mind. This means that the Norwegian government should take precautionary action that ensures the continuation of ecosystem services that support economic, environmental and social sustainability.

It is likely that, when compared to fish meal and SPC, acting precautionary by adding the Pacific oyster in feed will be beneficial in the long run. The alternative cost of doing nothing is much higher than the cost of preventing biodiversity loss (Millennium Ecosystem Assessment, 2005; TEEB, 2010). The use of Pacific oysters in salmon feed can prevent biodiversity loss both in the areas it is harvested and in the ecosystems from which fish meal and SPC originate. However, this implies that someone is ready to bear the cost of preventing biodiversity loss. At present, Storm Østers AS will not be able to sell its oysters to a salmon feed production company because they have competitors such as fish meal and SPC that are far more cost-effective. If a feed production company bears the cost, they will be outcompeted by the next feed company. In this case, if the Pacific oyster is to succeed as an ingredient in salmon feed, external forces, such as the government, need to get involved by subsidising the development of technology that can increase the catch and reduce the cost per tonne of oyster. Otherwise, the Pacific oyster needs to be allocated to markets with a higher willingness to pay.

As suggested by Eroldoğan et al. (2022), blue mussel meal have been fed to black soldier fly larvae to give them a favourable omega-3 profile. This is a potential market for the Pacific oyster, as it has a somewhat comparable nutrient profile with the blue mussel (Almås et al., 2020). Otherwise, pet food markets and cosmetics have high willingness to pay and could be explored (Dužević, 2023; Joung et al., 2014; Pearce et al., 2023). Some feed producers said that the Pacific oyster could potentially be used in organic feed, of which they produce about 20,000 to 30,000 tonnes a year. A use in ecological feed would still require a substantial scale up of harvesting.

The relevant hypothesis for this section is:
H_4: There is a gain from substituting the use of SPC and fish meal with the Pacific oyster by ensuring the continuation of ecosystem services.

Replacing the use of SPC and fish meal with Pacific oysters is a dual benefit because it ensures that ecosystem services can continue to be provided both in the areas where SPC and fish meal are sourced and in the areas where Pacific oysters are harvested. However, the feed producers have stated that they do not want to substitute any ingredients, especially marine ingredients, because they want to grow. This means that the Pacific oyster will not reduce the current reliance on unsustainable feed ingredients, but will, at best, reduce some of the increasing reliance on these ingredients. This does not, however, limit the positive impact of harvesting Pacific oysters in Norwegian waters on the continuation of ecosystem services. In other words, the hypothesis H_4 is strengthened.

8. Conclusion

8.1 Overall conclusion

The impact of the Pacific oyster on the ecosystems it invades is complex and multifaceted. Research on the invasion of the Pacific oyster in other countries shows results that cannot be generalised to other ecosystems, which means that there is no certainty about the effects of the invasion of the Pacific oyster on the Norwegian coast. Norway is obliged by law to act according to the precautionary principle when there is uncertainty about the effects of an IAS. Following the precautionary principle can ensure the continuation of important ecosystem services that provide humanity with food, medicine, building materials, recreation and climate regulation. By creating a value chain for the Pacific oyster harvested off the Norwegian coast, it is possible to ensure the continuation of ecosystem services in areas affected by harvesting for fish meal and soy cultivation, while at the same time ensuring the continuation of ecosystem services such as disease regulation, recreational value and food availability in the food web in the areas from which the Pacific oyster is harvested. By using the Pacific oyster in a value chain, the management of the IAS may become self-sufficient.

In this thesis, based on the nutrient profile of the Pacific oyster and the costs associated with harvesting, it was assessed whether a possible value chain for the Pacific oyster could be salmon feed. According to the results of the nutrient analysis and input from salmon feed producers, the Pacific oyster has a moderately interesting nutrient composition for use in salmon feed. The protein content (49.3% DW) is at the lower end of what feed manufacturers consider interesting for protein ingredients. The levels of EPA and DHA (0.71% DW) were of interest. However, there are uncertainties associated with these figures as the method of measuring protein is questionable and the effect on nutrient composition is influenced by the time of year the oysters are harvested.

The real challenge of using Pacific oysters in salmon feed is to reduce the cost of harvesting. With their current and planned technology, Storm Østers AS will not be able to harvest enough oysters to meet even the smallest amount of feed ingredient required by the feed manufacturers, which is about 200 tonnes per year. Even with their planned new technology, the harvesting company will have to harvest for almost 7 years to meet the annual demand of the feed producers. Many of these challenges are related to the high water content of the Pacific oyster.

An average two-year-old oyster has only on average 10.9% of obtainable dry matter. This means that the current price for dried oyster meal is NOK 825,688 per tonne, which is more than NOK 800,000 higher than the price of fish meal and SPC, which often has a 20–30% higher protein content. If Pacific oysters are to be used in salmon feed in the future, the general cost of feed ingredients will have to increase or the cost of harvesting will have to be reduced significantly. More cost-effective harvesting is likely to be possible with new technologies that can be developed with subsidies or investment.

Using the Pacific oyster in salmon feed contributes positively to sustainability, as it does not rely on arable land, fertiliser or water, while at the same time oyster harvesting contributes to the management of an IAS. However, if feed companies do not seek to replace ingredients, the best-case scenario is that the Pacific oyster will limit increased reliance on unsustainable feed ingredients, but will not contribute to a reduction in the use of these ingredients. The Pacific oyster needs to become an industry of scale before it is looking towards the salmon industry. Scale can hopefully decrease the price, increase the annual catch and allow the Pacific oyster to have a significant impact on the sustainability of the feed.

8.2 Implications and limitations

Implications of the study

The aim of this thesis was to evaluate the Pacific oyster in a market where no other studies has evaluated it before: salmon feed. This thesis helped to identify the challenges that need to be addressed if the Pacific oyster is to be included in salmon feed. The conclusion of this thesis is that there is no doubt that oysters need to be harvested at a much higher rate and at a much lower cost to be of interest to salmon feed producers. Further, this thesis is an example of the holistic thinking that needs to be applied to a greater extent in the research of novel feed ingredients. There are several important aspects that are not included in this work, but having a perspective on sustainability, nutritional suitability and cost is important to make effective decisions in a highly competitive industry.

The nutrient analysis carried out during the preparation of this thesis can be used as a means of identifying potential other markets for the oyster. A market with a higher willingness to pay, such as the pet food market could be interesting to explore. Also, exploring a market where carbohydrates are more in demand. In which case a more thorough analysis of carbohydrates should be carried out.

In this thesis it was found that feed producers are not interested in substituting their commonly used feed ingredients, especially not the marine ingredients. It shows that growth in the salmon farming industry does not make sense from a sustainability perspective. If the current use of feed ingredients is not sustainable and feed producers do not want to substitute these ingredients, but rather grow, sustainability will not improve.

Limitations of the study

Of the 70 articles included in the systematic literature review, only 23 were part of the original literature search. Given that the additional 49 were relevant, this may indicate that the search strings were poorly optimised. It is also possible that Web of Science did not have access to these articles, and a combination is possible. In this case, I could have worked with the search strings further to ensure that they covered more of what I wanted to research. On the other hand, this method allows for an exploratory literature search, but at the expense of replicability.

When looking at the summarised effects of the Pacific oyster invasion in table 2, it is evident that much of the research the systematic literature study is based on, is between 15 and 20 years old. In most cases, it was sought to obtain newer research, but it was not always possible. This means that there is a possibility that the information this thesis is based upon could be outdated and therefore not representative of the current state of the world.

When the interviews were conducted with the feed producers, they were given an analysis from NMBU and one from IVL. There was some confusion about the amount of EPA and DHA in the fat and the unit of measurement. For the second interview, I changed the unit of measurement, but this may have led to a different understanding between the participants, meaning that they gave their insights into the nutrient profile on a different basis, leading to imprecise results. This, in turn, can lead to poor replicability of the study. In this case, I should have understood the material I was presenting better and looked up the most common unit of measurement used in nutrient composition.

Some feed producers said that the Pacific oyster probably could not compete with bulk ingredients because it is not part of an industry of scale. This means that the Pacific oyster may have been compared to ingredients that have an unfair advantage in terms of price, and that it would be more logical to compare it to other ingredients that are used as additives rather than in bulk.

8.3 Recommendations for further research

There is limited knowledge of the effects of the invasion of the Pacific oyster on the Norwegian coast, and the research done on other European countries have somewhat diverging findings. To be able to develop the best management method, there needs to be more research on the effects of the Pacific oyster on the Norwegian coast.

To date, there is no research that gives a clear answer to the question of how many Pacific oysters can be found along the Norwegian coast. Obtaining this information will help in finding the right market for the Pacific oyster and should be investigated. However, the Pacific oyster has a high reproductive potential and is an ecosystem engineer, and the population is likely to increase significantly if no effective management is put in place.

The Pacific oyster does not compete well with bulk protein or EPA+DHA sources. Other feed ingredients, such as additives, could be explored. As pointed out by some feed producers, alternative feed ingredients like the Pacific oyster should be screened for a "factor x" that might make them interesting beyond meeting the nutritional needs of the salmon. Such factors could be nutrients that increase immune response or otherwise reduce mortality, or, as pointed out by the feed producers, it could be an interesting natural sources of zinc and vitamin C.

In order to argue for the inclusion of Pacific oysters in feed on the basis of increased sustainability, there needs to be comparable figures with current knowledge of the sustainability of common feed ingredients. Such a tool could be an LCA, and should be prioritised as the oyster industry reaches scale in order to get as accurate a picture of sustainability as possible.

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Appendices:

Appendix 1: Interview question template

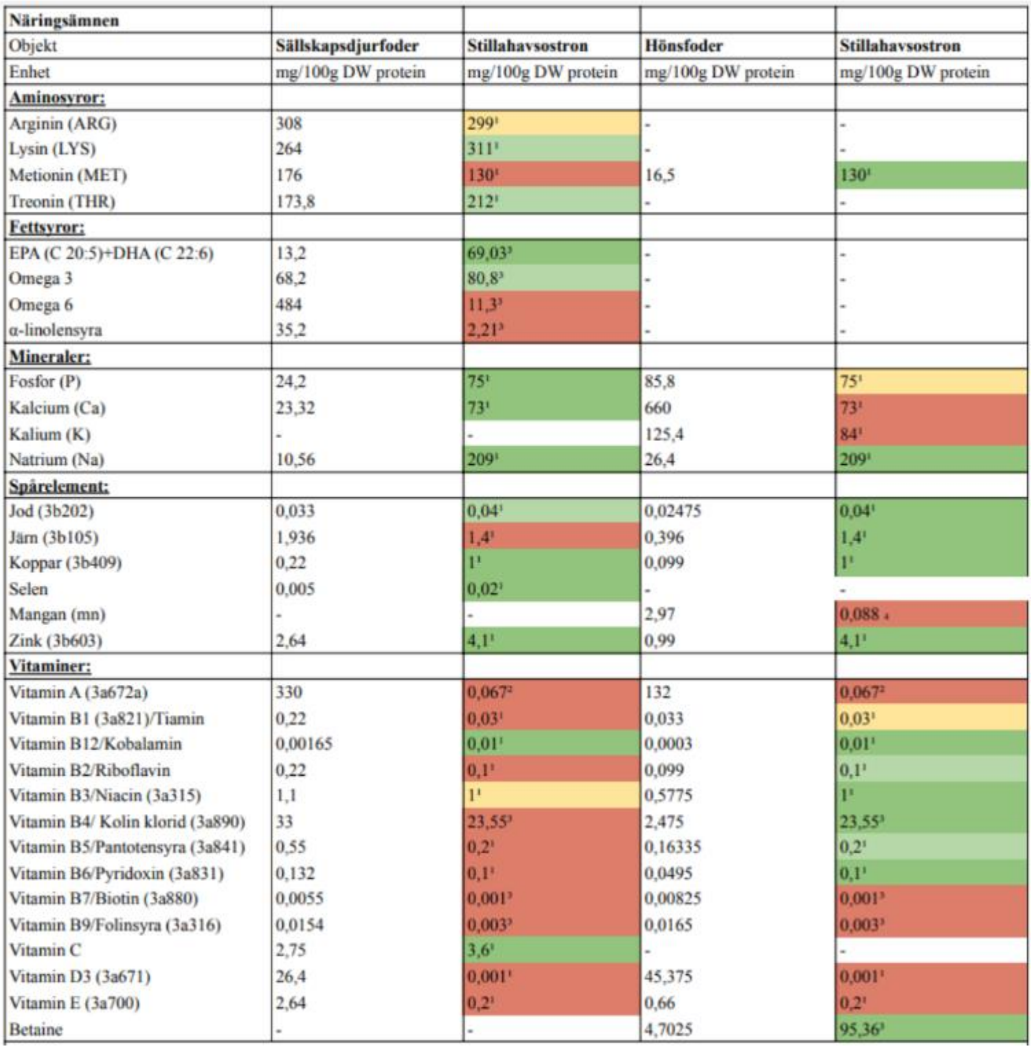
Questions for feed producers:

1. What is the smallest volume of the Pacific Oyster you have to offer for it to be interesting on a commercial scale?
2. When you look at the nutrient profile of the Pacific Oyster, do you think it could substitute the oil- or protein fraction in the feed? Why?
3. After seeing these analyses, what price do you think your company would be able to pay for 1% inclusion of the Pacific Oyster? How does the sustainability profile impact the price you are willing to pay?
4. What are the most important aspects you consider when you evaluate potential new feed ingredients?
5. What are your thoughts on the feed ingredients of the future?
6. How do you think the pacific oyster will impact the sustainability of your feed?
7. What are the main opportunities and challenges you can think of regarding using the pacific oyster in feed?

Questions for oyster harvester:

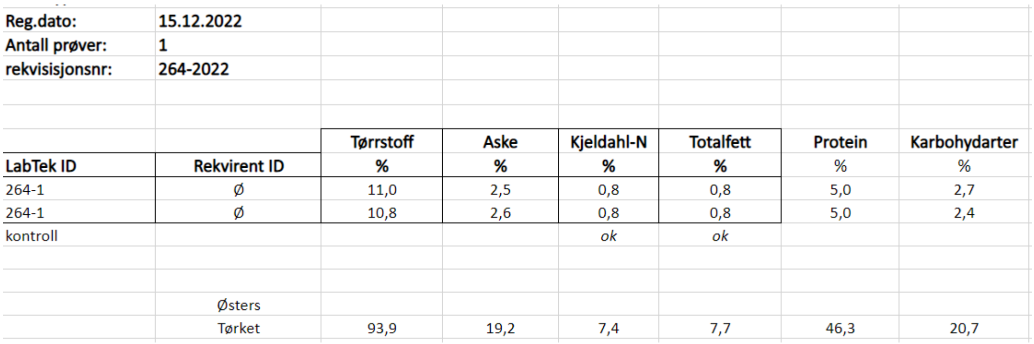
1. How many oysters do you harvest per labour hour?
2. What is your harvesting strategy? Do you pick strategically in a way that ensures good recruitment in the next season? Do you clear an area before moving on to the next?
3. What does it take for you to be allowed to harvest in an area?
4. What is the current price per tonne for Pacific oysters? Is this price including shells?
5. Have you done any analyses on *catch per unit effort*?
6. What are the main cost drivers?
7. What do you consider as possible solutions to reduce costs?
8. Do you currently harvest Pacific oysters that are not suitable for human consumption? What do you do with them?
9. How much of the Pacific oysters that are out there do you think will be unfit for human consumption when harvested?
10. What do you think it would take to make production more efficient (more oysters/time)?

Appendix 2: Analyses shown feed producers during interviews



Näringsämnen				
Objekt	**Sällskapsdjurfoder**	**Stillahavsostron**	**Hönsfoder**	**Stillahavsostron**
Enhet	mg/100g DW protein	mg/100g DW protein	mg/100g DW protein	mg/100g DW protein
Aminosyror:				
Arginin (ARG)	308	299^1	-	-
Lysin (LYS)	264	311^1	-	-
Metionin (MET)	176	130^1	16,5	130^1
Treonin (THR)	173,8	212^1	-	-
Fettsyror:				
EPA (C 20:5)+DHA (C 22:6)	13,2	69,03^3	-	-
Omega 3	68,2	80,8^3	-	-
Omega 6	484	11,3^3	-	-
α-linolensyra	35,2	2,21^3	-	-
Mineraler:				
Fosfor (P)	24,2	75^1	85,8	75^1
Kalcium (Ca)	23,32	73^1	660	73^1
Kalium (K)	-	-	125,4	84^1
Natrium (Na)	10,56	209^1	26,4	209^1
Spårelement:				
Jod (3b202)	0,033	0,04^1	0,02475	0,04^1
Järn (3b105)	1,936	1,4^1	0,396	1,4^1
Koppar (3b409)	0,22	1^1	0,099	1^1
Selen	0,005	0,02^1	-	-
Mangan (mn)	-	-	2,97	0,088 $_4$
Zink (3b603)	2,64	4,1^1	0,99	4,1^1
Vitaminer:				
Vitamin A (3a672a)	330	0,067^2	132	0,067^2
Vitamin B1 (3a821)/Tiamin	0,22	0,03^1	0,033	0,03^1
Vitamin B12/Kobalamin	0,00165	0,01^1	0,0003	0,01^1
Vitamin B2/Riboflavin	0,22	0,1^1	0,099	0,1^1
Vitamin B3/Niacin (3a315)	1,1	1^1	0,5775	1^1
Vitamin B4/ Kolin klorid (3a890)	33	23,55^3	2,475	23,55^3
Vitamin B5/Pantotensyra (3a841)	0,55	0,2^1	0,16335	0,2^1
Vitamin B6/Pyridoxin (3a831)	0,132	0,1^1	0,0495	0,1^1
Vitamin B7/Biotin (3a880)	0,0055	0,001^3	0,00825	0,001^3
Vitamin B9/Folinsyra (3a316)	0,0154	0,003^3	0,0165	0,003^3
Vitamin C	2,75	3,6^1	-	-
Vitamin D3 (3a671)	26,4	0,001^1	45,375	0,001^1
Vitamin E (3a700)	2,64	0,2^1	0,66	0,2^1
Betaine	-	-	4,7025	95,36^3

Analysis done by IVL. Table made by Mathilda Nyquist.



Reg.dato:	**15.12.2022**						
Antall prøver:	**1**						
rekvisisjonsnr:	**264-2022**						
		Tørrstoff	**Aske**	**Kjeldahl-N**	**Totalfett**	**Protein**	**Karbohydrater**
LabTek ID	**Rekvirent ID**	**%**	**%**	**%**	**%**	%	%
264-1	Ø	11,0	2,5	0,8	0,8	5,0	2,7
264-1	Ø	10,8	2,6	0,8	0,8	5,0	2,4
kontroll				*ok*	*ok*		
	Østers						
	Tørket	93,9	19,2	7,4	7,7	46,3	20,7

Analysis done by NMBU

Appendix 3: Calculations for price per tonne dried oyster meal

According to Bjørge at Storm Østers AS, Norwegian oysters are sold at 15,000 NOK per tonne. This is a price for whole oysters, while what has been analysed in this thesis is the meat. According to Fujiya (1970), at two years of age, an oyster without its shell is expected to weigh between 10 and 30g, with an average of 20g. A yield of 120 tonnes whole oysters include 20 tonnes of meat and 100 tonnes of shell. This leaves 1:5 ratio between oyster meat and oyster shell, and an equation:

x weight oyster/6 = x weight oyster meat

Price per tonne oyster meat

Norwegian oysters are sold at 15,000 NOK per tonne and per tonne whole oyster, 1:6 is meat. This results in this price per tonne oyster meat:

15,000 NOK per (tonne whole oysters / 6)
15,000 NOK / (1/6) = 90,000 NOK per tonne oyster meat

Price per tonne dried oyster meal

In this thesis, it was found that oyster meat contains on average 10.9% dry matter. This leaves a price per tonne dried oyster meal:

90,000 NOK / 10.9% = **825,688 NOK per tonne dried oyster meal**

In comparison, the current price for fish meal is $1,720.35 per tonne = 17,726 NOK per tonne and for SPC the price is about 9,000 NOK per tonne (Almås et al., 2020; IndexMundi, 2023) .

Appendix 4: Calculations of the amount of oysters and time needed to harvest based on current harvesting rate

Number of oysters that need to be harvested:

If the average oyster weight, without shell, is about 20g and the salmon feed manufacturers want a minimum of 200 tonnes yearly, Storm Østers AS needs to harvest:

200 tonnes / 20 g = 10,000,000 oysters

However, this is unprocessed oysters. The Pacific oyster used in this thesis consists of 10.9% dry matter. This leaves us with a dry matter yield per oyster:

20g * 10.9% = 2.18 g

To satisfy the feed producers need of 200 tonnes, Storm Østers AS need to harvest:

200 tonnes / 2.18 g **= 91,743,119 oysters**

Time needed to harvest minimum amount for salmon feed:

Currently, Storm Østers AS is able to harvest 600 shells every hour, but hope to increase it to 4 tonnes each day with the new technology.

With current technology:

Assuming 8 hour work days, and harvest 365 days a year.

91,743,119 / (600*8h) = 19,113 days **= 52 years**

With new technology:

Assuming harvest 24/7/365.

The average oyster weighs 20g + (20g*5) = 120g.

The number of oysters the harvesting company will be able to harvest with the new technology:

4 tonnes/ 120g = 33,333 oysters each day.

To reach 91,743,119 oysters, the harvesting company needs to harvest for this number of days:
91,743,119 oysters / 33,333 oysters each day = 2,752 days **= 7.5 years**

Year round, Storm Østers AS is able to harvest:
33,333 * 365 = 12,166,545 oysters
4 tonnes * 365 * (1/6) * 10.9% = 26.5 tonnes dried oyster meal (DW)

This estimate is very rough, as the oysters that are harvested with the end goal of being used feed, not as a delicacy, might be substantially larger than the two-yearlings that are used as baseline here. This means that the numbers of oysters that need to be harvested to satisfy the demand of feed producers might be lower. Additionally, it was assumed that the new technology would be able to run 24/7, which is likely not the case as it might need maintenance. Meaning, the actual number of oysters harvested per time with the new technology is likely a bit lower.

These results show that Storm Østers AS will not be able to satisfy the lowest yearly required amount of dried oyster meal, even when running the new technology 24/7.

Appendix 5: Value of one tonne protein, EPA/DHA from dried oyster meal when compared with fish meal, SPC and fish oil

Compared to the price of fish meal

Our dried oyster meal consists of 49.3% protein. The fish meal used in the comparison of ingredients consists of 74.8% protein (Feedtables, n.d.a). Fish meal costs 17 725.75 NOK per tonne (IndexMundi, 2023). The value of protein content in dried oyster meal if compared to fish meal:

74.8% = 17,725.75 NOK
49.3% = x NOK

(17,725.75 * 49.3) / 74.8 = <u>11,683 NOK per tonne</u>

The value of one tonne of the protein in the Pacific oyster is 11,683 NOK when compared to the protein in fish meal. This means that it is about 6,000 NOK less valuable per tonne than fish meal when considered as a protein source.

Compared to the price of soy protein concentrate

Our dried oyster meal consists of 49.3% protein. The SPC used in the comparison of ingredients consists of 84.4% protein (Feedtables, n.d.b). SPC costs approximately 9000 NOK per tonne (Almås et al., 2020). The value of protein content in dried oyster meal if compared to SPC:

84.4% = 9,000 NOK
49.3% = x NOK

(9,000 * 49.3) / 84.4 = <u>5,257 NOK per tonne</u>

The value of one tonne of the protein in the Pacific oyster is 5,257 NOK when compared to the protein in SPC. This means that it is about 4,000 NOK less valuable per tonne than SPC when considered as a protein source.

Value of one tonne EPA/DHA from dried oyster meal when compared to fish meal

The dried oyster meal consists of 0.71% EPA/DHA. The fish meal used in the comparison of ingredients consists of 1.12% EPA/DHA (Feedtables, n.d.a). Fish meal costs 17,725.75 NOK per tonne (IndexMundi, 2023). The value of EPA/DHA content in oyster meal if compared to EPA/DHA content in fish meal:

1.12% = 17,725.75 NOK
0.71 % = x NOK

(17,725.75 * 0.71) / 1.12 <u>= 11,237 NOK per tonne</u>

Value of one tonne EPA/DHA from oyster meal when compared to fish oil

The dried oyster meal consists of 0.71% EPA/DHA. The fish oil used in the comparison of ingredients consists of 18-27% EPA/DHA (Almås et al., 2020). Fish oil costs 18,110.33 NOK per tonne (Statista, 2023). The value of EPA/DHA in dried oyster meal compared to EPA/DHA content in fish oil:

Low EPA/DHA content in fish oil
18% = 18,110.33 NOK
0.71 % = x NOK

(18 110.33 * 0.71) / 18 <u>= 714 NOK per tonne</u>

High EPA/DHA content in fish oil
27% = 18,110.33 NOK
0.71 % = x NOK

(18 110.33 * 0.71) / 27 <u>= 476 NOK per tonne</u>

The value of the EPA/DHA content in the Pacific oyster is 714–476 NOK when compared to the EPA/DHA in fish oil. This means that it is about 17,500 NOK less valuable per tonne than fish oil when considered as a source for EPA/DHA.

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