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Higher dietary EPA & DHA levels improve commercial salmon farming productivity, predictability and sustainability

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As aquaculture production has grown to meet rising demand for healthy seafood, the demand for aquaculture feed has increased substantially, placing greater pressure on finite marine ingredient resources. Periods of fish oil shortage, such as during the 2023–2024 El Niño, can reduce dietary levels of the essential omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), negatively affecting salmon farming performance. This large-scale observational study analyzed more than 430 million Atlantic salmon (556 generations) to quantify the relationship between dietary EPA+DHA levels and commercial production outcomes. Using population tracing and Inverse Probability Weighted Regression Adjustment, the study found positive responses for populations receiving higher dietary EPA+DHA levels (>9%TFA, total fatty acids). The positive responses included lower mortality (–8%), improved economic feed conversion ratio (eFCR; –13%), and higher harvest quality (+2%) compared with populations receiving lower levels (<7%TFA). Higher EPA+DHA levels were also associated with greater production predictability. Variability in mortality, eFCR, and harvest quality was reduced, with coefficients of variation declining by 50%, 27%, and 29%, respectively. These improvements narrowed the uncertainty associated with environmental stressors contributing to more consistent performance under commercial conditions. Scenario modelling assessed the impact of increasing dietary EPA+DHA from 6% to 10% using Veramaris® algal oil. The resulting biological improvements reduced the carbon footprint and marine footprint of harvested salmon by 17% and 15%, respectively. These gains generated a positive return on investment through better survival, feed efficiency, and harvest quality. Overall, the results indicate that higher dietary EPA+DHA levels can improve the profitability, stability, and sustainability of commercial salmon aquaculture.

KEYWORDS
algal oil, aquaculture, Atlantic salmon, EPA+DHA, feed efficiency, harvest quality, survival

1 Introduction

Global aquaculture is a cornerstone of food security, recently reaching a historic milestone where its production surpassed capture fisheries to provide 52.77% of the world's aquatic animal food (Albrektsen et al., 2022; FAO, 2026). Atlantic salmon (*Salmo salar*) is a key species within this sector, recognized as a resource-efficient source of high-quality protein and essential nutrients (Santigosa et al., 2023b; FAO, 2026). In particular, farmed salmon represents a major source of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) for human nutrition (Horn et al., 2019), which are essential for cardiovascular health and cognitive development (Calder, 2017; Horn et al., 2019; Martins et al., 2020; Bernasconi et al., 2021; Zatti et al., 2023; Carr et al., 2024).

However, the sector is under increasing pressure to improve both production efficiency and environmental sustainability, particularly related to resource use and carbon footprint. A major constraint to achieving these goals lies in feed formulation. Historically, fish oil (FO) derived from wild-caught forage fish was the primary source of EPA and DHA in aquafeeds (Aas et al., 2019) and has reached a global production plateau of approximately one million tons annually, limiting its scalability and becoming a significant bottleneck for industry growth (Zatti et al., 2023).

To sustain production growth and control diet costs, vegetable oils (VOs) have been increasingly incorporated into aquafeeds. While this transition has supported scalability, it has also altered the dietary fatty acid profile of feeds, as VOs are typically low in long-chain omega-3 fatty acids, including EPA and DHA, and high in omega-6 fatty acids. This shift has contributed to changes in essential fatty acid profiles, which have been associated with altered metabolic, immune, and physiological responses in fish (Albrektsen et al., 2022; Carr et al., 2024). The deposition of EPA and DHA in salmon fillets is closely linked to levels delivered in the feed. Consequently, EPA and DHA levels in farmed salmon have declined substantially over recent decades, with reductions of more than 50% reported in fillet composition, and dietary inclusion often maintained near minimum biological requirements (~1% of the diet or 3% to 5% of total fatty acids (TFA)) (Nichols et al., 2014; Sprague et al., 2020; Aas et al., 2022; Albrektsen et al., 2022). Such reductions also influence biological performance and production efficiency, particularly under commercial farming conditions where fish are exposed to multiple environmental and biological stressors.

At the production level, biological performance remains a critical constraint to industry sustainability. Mortality-related losses in Norway alone are estimated to exceed $1 billion annually, illustrating the economic impact of suboptimal robustness (Moldal et al., n.d). From a systems perspective, reduced performance translates into lower resource-use efficiency, as higher feed inputs and production losses increase the environmental footprint per unit of harvested fish. In addition, the aquaculture sector faces broader systemic challenges, including supply-chain disruptions, price volatility, and increasing scrutiny of environmental impacts. These factors further challenge the long-term sustainability and "license-to-operate" of the sector (Albrektsen et al., 2022; Goglio et al., 2022; Santigosa et al., 2023b).

In this context, nutritional strategies are increasingly recognized as a key lever to improve both productivity and sustainability of salmon farming. Increasing dietary EPA+DHA levels has been shown to support growth, survival, and product quality, particularly under challenging conditions (Bou et al., 2017; Løvmo et al., 2021; Ruyter et al., 2022; Carr et al., 2023; Lutfi et al., 2022). The development of alternative sources of EPA and DHA, including microalgae-derived oils, provides scalable pathways to restore omega-3 levels in aquafeeds while reducing reliance on finite marine resources (Santigosa et al., 2023b). These alternative sources allow for the implementation of higher dietary EPA+DHA levels, which have been associated with biological improvements in previous studies (Carr et al., 2024).

Despite these advances, a key limitation remains in translating nutritional improvements into consistent outcomes under commercial farming conditions. Laboratory and controlled studies are limited by scale and scope and do not fully capture the complexity of real-world aquaculture systems, where variability in environmental conditions, management practices, disease pressure, and biological characteristics introduce significant confounding effects.

Big data (BD) approaches offer a pathway to address these limitations by integrating feed composition, production, and performance data across multiple farms and production cycles (Neethirajan, 2020; Tao et al., 2021). Building on previous large-scale observational analyses (Carr et al., 2024) this study introduces methodological advancements designed to improve the robustness and interpretability of commercial production data. Using an expanded dataset of over 430 million Atlantic salmon, this study applies: (i) population-level tracing to define cohorts with shared production histories, (ii) Inverse Probability Weighted Regression Adjustment (IPWRA) to account for confounding factors, and (iii) variability-based metrics to assess the predictability of production outcomes. The objective of this study was to evaluate the association between dietary EPA+DHA levels and biological performance, production efficiency, and environmental impact under commercial Norwegian salmon farming conditions, while advancing analytical approaches for the interpretation of large-scale aquaculture datasets.

2 Methods

2.1 Dataset and dietary EPA+DHA categorization

The present observational BD study utilized a large-scale commercial dataset consisting of 556 generations of Atlantic salmon, representing over 430 million salmon produced across Norwegian production areas 2–10 between 2013 and 2023. Feed characteristics, specifically EPA+DHA content (expressed as percentage of TFA), were integrated with production data, allowing each production unit to be associated with the EPA+DHA content of the feed used during the production cycle.

Dietary categorization was based exclusively on EPA+DHA levels. Other nutritional characteristics (e.g., total lipid content,

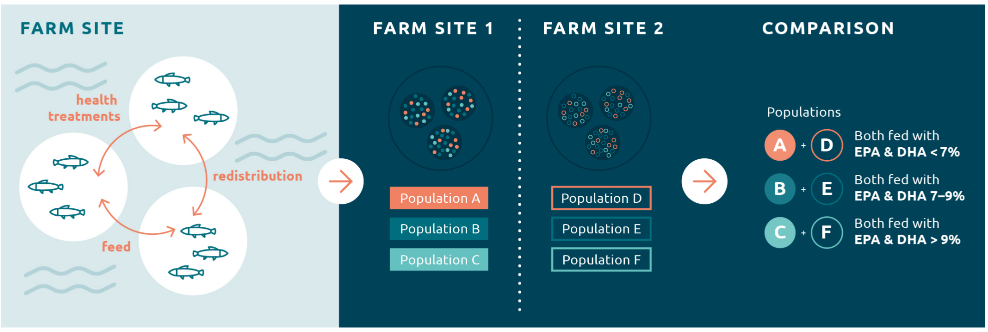


FIGURE 1
Illustration of tracing and grouping at the population level.

protein levels, or energy density) were not available in a harmonized format across the dataset and were therefore not included as covariates. To analyze the relationship between dietary EPA +DHA levels and production outcomes, the generations were classified into three distinct categories based on the weighted average percentage of EPA+DHA relative to TFA in the diet: below average, <7%; average, 7% to 9%; and above average, >9%. Processor-level records were also included to assess post-harvest fillet quality attributes, specifically melanin spot and blood spot prevalence. To analyze the relationship between dietary EPA+DHA levels and fillet quality outcomes, the data was classified into three categories based on the weighted average percentage of EPA+DHA relative to TFA in the diet: below average, <7%; average, 7% to 8%; and above average, >8%. Production level data and processor level data were obtained from independent sources and the respective thresholds were selected to reflect commonly observed ranges in commercial feed formulations, and to ensure sufficient sample size within each category for statistical comparison. As a result, adjusted comparisons were restricted to the below-average and above-average EPA+DHA categories, where overlap between treatment groups was sufficient to support more reliable estimation of adjusted effects.

2.2 Population tracing

A primary challenge in analyzing commercial "big data" in aquaculture is the inherent variability in farming conditions. Even within the same farm, individual fish experience different production histories and life cycles. Failure to adequately account for this heterogeneity may result in "Simpson's paradox", a statistical phenomenon in which trends observed within separate groups change or disappear when the groups are combined (Simpson, 1951).

To address this issue, fish were algorithmically traced through production records from stocking to harvest and grouped into populations based on shared production histories, including, but not restricted to, treatment history, vaccination protocols, environmental exposure, and smolt characteristics (Figure 1). Each population represented a cohort of fish with relatively homogeneous biological and production conditions over time. Multiple populations were identified within individual farm sites, reflecting the differences in fish origin, stocking timing, movement history, or management practices. All analyses and comparisons were conducted at the population level to reduce within-group heterogeneity and improve comparability between groups exposed to similar production conditions.

2.3 IPWRA and predictability assessment

The population-structured datasets were analyzed using IPWRA, a doubly robust causal inference approach commonly used in observational studies where treatment assignment is non-random. IPWRA models both the (i) probability of a population receiving a specific dietary level, through the treatment-assignment model, and (ii) resulting performance outcomes, through the outcome-regression model. The treatment-assignment component builds on the propensity score framework (Rosenbaum and Rubin, 1983) while the combined use of treatment and outcome models follows the doubly robust estimation approach (Funk et al., 2011). This approach was appropriate for the present field dataset because dietary EPA+DHA levels were not randomly assigned but instead reflected commercial feed-use patterns across production zones, time periods, and population characteristics.

IPWRA therefore allowed comparisons between dietary groups to be adjusted for observed differences in production context while retaining the scale and heterogeneity of real-world salmon farming data. In practical terms, this means the method can provide reliable adjusted comparisons if either the model describing dietary group assignment or the model describing production outcomes is adequately specified, provided the main measured differences between populations are included in the analysis. Covariates in the treatment-assignment and outcome-regression models comprised operational and health-related production variables: smolt size, time in sea, feeding rates, environmental exposure, sea lice treatment history, vaccination protocols, disease incidence, parasite pressure, and prior mortality patterns. Nutritional covariates were limited to total dietary EPA+DHA (%TFA) as this was the only feed characteristic available in a harmonized form across the dataset. Other diet components (e.g. lipid level, energy density, other fatty acids, micronutrients, etc.) were not incorporated and are addressed as a study limitation in Section 4.

Model robustness was assessed via the composite profile-overlap check described in Section 2.1, which supported restricting adjusted comparisons to the below-average and above-average EPA+DHA categories. The analysis was conducted in two stages:

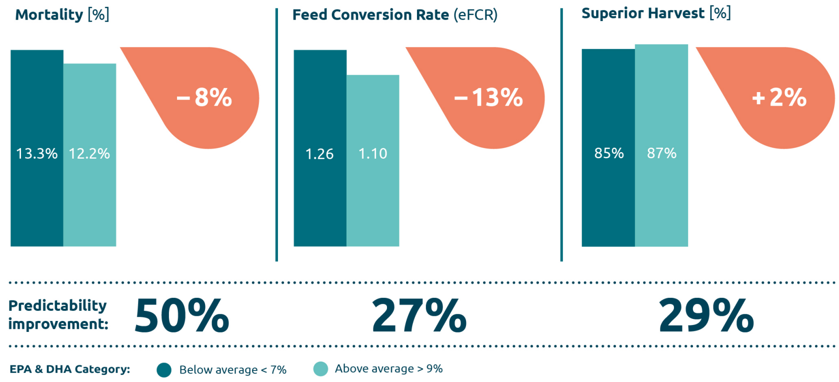


FIGURE 2
Improvement in the % mortality, eFCR and % of fish classified as "superior harvest" grade and the predictability of these metrics.

first, develop a treatment model to estimate the probability of assignment to each EPA+DHA category. Subsequently, incorporate those estimated probabilities into an outcome model via inverse probability weighting to produce adjusted efficacy comparisons between dietary groups. The outcome models estimated adjusted mean differences in mortality, eFCR, and harvest quality between dietary EPA+DHA categories.

Predictability was assessed by quantifying within-group variability for each outcome using variance and coefficient of variation (CV). Relative improvements in predictability were calculated as percentage reductions in CV between dietary EPA+DHA categories.

2.4 Biological modelling

Biological performance was assessed via survival (total mortality percentage) and feed efficiency (economic Feed Conversion Ratio, eFCR).

2.5 Harvest and fillet quality assessment

Harvest quality was assessed based on the percentage of "Superior Harvest" graded salmon. Fillet quality was assessed based on the prevalence of downgrading factors, namely melanin spots and blood spots. The processor dataset provided for fillet quality was analyzed using the previous analytics engine (Carr et al., 2024). IPWRA was not applied to evaluate fillet quality because, unlike the farmer data, processor data was not structured at the population level.

2.6 Environmental impact modelling

A complementary component of this study was the quantification of environmental impacts using the Sustell™ platform. A comparative Life Cycle Assessment (LCA) was conducted to evaluate the environmental implications of using Veramaris® algal oil to increase dietary EPA+DHA levels from 6% to 10% TFA in the grow-out phase under modelled scenarios. Environmental impacts were quantified in terms of carbon footprint (kg CO_2-equivalent/kg of harvested salmon). In addition, marine footprint (calculated as (% fish oil in feed from forage fisheries*FCR)/5.0), is expressed as the Forage Fish Dependency Ratio for oil (FFDRoil).

2.7 Economic modelling

Economic performance was evaluated using a modelled return on investment (ROI) framework. The economic model was based on a commercial production scenario assuming an initial smolt weight of 300g and a harvest weight of 5kg, with cumulative mortality losses equivalent to 1.4kg of live weight. Feed cost was set at $1,800/metric ton, while market price was assumed to be $7.50/kg for superior quality fish, with a discount of $0.19/kg applied to downgraded fish. ROI was calculated by comparing the incremental cost of increasing dietary EPA+DHA levels with the modelled economic benefits associated with observed changes in mortality, eFCR, and harvest quality. The ROI analysis is a scenario-based model dependent on input assumptions, including feed costs and market prices, which may vary across regions, production systems and years.

3 Results

3.1 Biological modelling

The IPWRA analysis indicated that higher dietary EPA+DHA levels (>9%) were associated with improved performance outcomes compared to lower levels (<7%), both in terms of mean values and variability. Total mortality was 8% lower in populations receiving EPA+DHA levels >9% (12.2%, interquartile range (IQR) 6.1-16.5%) compared to those receiving <7% (13.3%, IQR 4.1-18.7%, Figure 2). This reduction was accompanied by a 50% decrease in variability (CV), indicating improved predictability of mortality outcomes across populations. Similarly, eFCR was reduced by 13%, from 1.26 (IQR 1.00-1.55) to 1.10 (IQR 0.89-1.26), in salmon fed EPA+DHA levels >9% compared to those fed EPA+DHA levels <7% (Figure 2), and this improvement was associated with a 27% reduction in variability.

3.2 Harvest quality modelling

In addition, harvest data showed a positive association between EPA+DHA levels >9% and the commercial value of the final

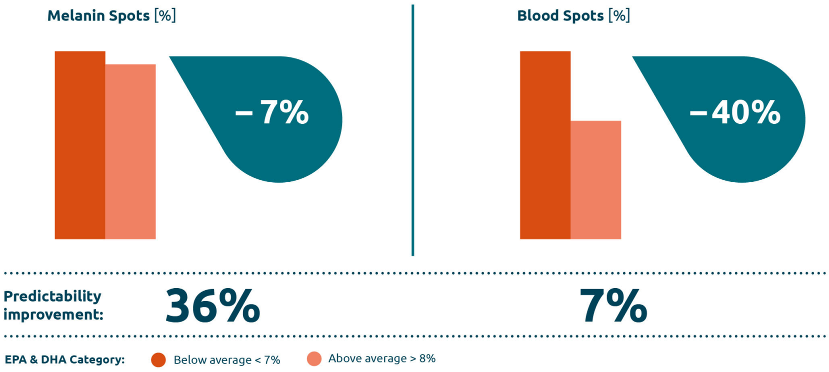


FIGURE 3
Improvement in the % of melanin spots and blood spots and the predictability of these metrics.

product. Populations receiving higher EPA+DHA levels produced 2% more fish classified as "Superior Harvest" grade, and the predictability of this improvement was associated with a 29% reduction in variability (Figure 2).

3.3 Fillet quality data

The prevalence of melanin spots and blood spots in fish fed EPA +DHA levels >8% was reduced by 7% and 40%, respectively, compared to those fed EPA+DHA levels <7% and these reductions were accompanied by decreases in variability of 36% and 7%, respectively (Figure 3).

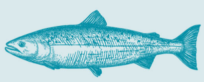
3.4 Environmental impact modelling

Under the modelled scenario, using Veramaris algal oil to increase dietary EPA+DHA levels from 6% to 10% TFA resulted in a 2.2% increase in the carbon footprint of feed (from 2.27kg to 2.32kg CO_2eq/kg feed). This led to a 1.2% increase in the carbon footprint of salmon produced to a harvest weight of 5kg (from 4.87kg to 4.93kg CO_2eq/kg harvested). However, when the reductions in mortality (−8%) and eFCR (−13%) achieved in the groups fed EPA+DHA levels >9% were incorporated into the model, the modelled carbon footprint of harvested salmon decreased by 17% (from 4.93kg to 4.10kg CO_2eq/kg harvested) and the FFDRoil by 15% (from 1.30 to 1.10; Figure 4).

Importantly, even a 1% improvement in both mortality and eFCR reduced the carbon footprint and FFDRoil by 2%, while greater improvements in either parameter resulted in progressively larger reductions in carbon and marine footprint (Figure 4). Scenario analysis indicated that feed efficiency was the primary driver of reductions in FFDRoil under the modelled conditions (Figure 4).

3.5 Economic modelling

ROI was modelled as a function of EPA+DHA unit cost ($/%/mT), incorporating observed productivity-related benefits. The ROI model was based on key production assumptions including, 300g live weight equivalent (LWE) smolt, 5kg harvest LWE, 1.4kg mortality LWE, $1800/mT feed cost, $7.50/kg price for head-on-gutted (HOG) superior quality fish and $0.29/kg discount for downgraded HOG fish. ROI decreased as EPA+DHA unit cost increased. At lower EPA+DHA costs, ROI values approached ninefold, however, the ROI remains positive within the full range of typical unit cost for EPA+DHA (Supplementary Image 1).



		Improvement in mortality			
		Carbon Footprint		FFDRoil	
		1%	8%	1%	8%
Improvement in eFCR	1%	*4.84* −2%	*4.52* −8%	*1.28* −2%	*1.28* −2%
	13%	*4.40* −11%	*4.10* −17%	*1.10* −15%	*1.10* −15%
	Baseline:	*4.93 kgCO2e/kg harvested*		*FFDRoil 1.30*	

FIGURE 4
Improvement in the carbon footprint and FFDRoil of 5 kg salmon at harvest assuming improvements in eFCR and mortality.

4 Discussion

The challenge of optimizing dietary EPA+DHA levels in Atlantic salmon during the grow-out phase is closely linked to the economic realities of modern aquaculture. Feed represents the largest operational cost for salmon producers, making dietary optimization a critical factor for biological performance and commercial viability (Albrektsen et al., 2022). Historically, variability in controlled experimental outcomes and the limited integration of biological, environmental and economic metrics have contributed to uncertainty regarding the adoption of higher dietary EPA+DHA levels (Carr et al., 2024). Consequently, optimal EPA+DHA inclusion levels remain debated across the industry, and strategies differ between salmon farms. Recent developments in alternative omega-3 sources, including microalgae-derived oils and genetically modified seed oils, have enabled the exploration of higher EPA+DHA inclusion strategies under commercial conditions (Zatti et al., 2023; Samuelsen et al., 2024). Results of this large-scale observational study indicate that higher dietary EPA+DHA levels (>9%) are associated with improved productivity and harvest quality under commercial Atlantic salmon farming conditions.

The 8% reduction in total mortality observed in the “Above Average” group (EPA+DHA>9%) aligns with the well-established roles of long-chain omega-3 fatty acids in immune and metabolic processes (Ortega-Gómez et al., 2013; Tocher, 2015; Saini and Keum, 2018; Punia et al., 2019; Oliver et al., 2020). While historically defined dietary EPA+DHA levels (3–5% TFA) were established to prevent deficiency, these levels may not fully support optimum physiological robustness under commercial farming conditions (Zatti et al., 2023; Glencross et al., 2024). In particular, such levels may be insufficient to support performance under modern production challenges, including thermal variability, handling stress, and disease pressure (Albrektsen et al., 2022; Santigosa et al., 2023b; Farris et al., 2024). Controlled experimental studies have reported variable effects of EPA+DHA on mortality (Sissener et al., 2016; Bou et al., 2017; Ruyter et al., 2022; Selvam et al., 2022; Lutfi et al., 2022), whereas large-scale observational analyses have reported reductions in mortality at higher EPA+DHA levels (Carr et al., 2024), which is consistent with the magnitude of reduction observed in the present study (8%). These findings suggest that higher dietary EPA+DHA levels may contribute to improved survival under commercial conditions, although causality cannot be fully established due to the observational nature of the dataset. In addition, a 50% reduction in variability was observed in populations receiving higher EPA+DHA levels. This indicates improved predictability of mortality outcomes across heterogeneous production environments and suggesting that higher EPA+DHA levels might support higher robustness under heterogeneous commercial farming conditions, consistent with the recognized role of these fatty acids in salmon health (Lutfi et al., 2022).

Beyond their association with survival, these findings suggest that high dietary EPA+DHA levels positively influence commercial salmon farm productivity, specifically feed efficiency. The 13% improvement in eFCR observed in the “Above Average” group (EPA+DHA>9%) is consistent with more efficient feed utilization associated with higher dietary EPA+DHA levels, in agreement with previous large-scale analyses reporting similar improvements (~11%) under comparable conditions (Carr et al., 2024). From a physiological perspective, EPA and DHA play important roles in membrane structure and function, influencing nutrient transport, metabolic efficiency, and energy partitioning (Santigosa et al., 2023b; Zatti et al., 2023; Samuelsen et al., 2024). These mechanisms enhance digestive efficiency and reduce metabolic costs associated with stress and inflammation, thereby improving feed conversion into biomass (Albrektsen et al., 2022; Farris et al., 2024). Consistent with these effects, the 27% reduction in variability in eFCR observed in this study indicates more stable feed utilization across populations exposed to heterogeneous production conditions. Which suggests that higher dietary EPA+DHA levels contribute to more consistent metabolic performance under variable environmental and management conditions. This increased predictability is particularly relevant in commercial aquaculture systems, where environmental variability, health challenges, and management practices differ across sites and production cycles. Therefore, achieving and maintaining higher dietary EPA+DHA levels in salmon feeds may support the implementation of nutritional strategies aimed at improving both efficiency and predictability in commercial salmon production.

Such improvements in metabolic efficiency may also have downstream implications for product quality at harvest. In line with this, dietary EPA+DHA levels were associated with differences in harvest quality. The 2% increase in superior-grade fish and the reduction in melanin spots (−7%) and blood spots (−40%) are consistent with reductions in key quality defects affecting commercial value in salmon production. These results are in agreement with previous studies reporting improved fillet integrity and pigmentation at higher dietary EPA+DHA levels (including through new omega-3 sources) (Mueller et al., 2023; Santigosa et al., 2023b). The reduction in localized tissue defects may be linked to the well-established role of EPA and DHA in modulating inflammatory responses. Melanin spots in salmon fillets are often the clinical manifestation of chronic inflammation (pleuritis or focal myositis), where incomplete resolution of tissue damage leads to persistent lesions (Santigosa et al., 2023b). Higher EPA+DHA levels may therefore support the regulation and resolution of these inflammatory processes through their role as precursors to specialized pro-resolving mediators, thereby reducing the likelihood of permanent tissue discoloration (Mueller et al., 2023). Similarly, the 40% reduction in blood spots may reflect improved structural integrity of vascular tissues and cellular membranes, which has been associated with omega-3 fatty acid composition (Farris et al., 2024). The present results also align with previous large-scale observations (Carr et al., 2024), which reported improved color scores and fewer downgrade-inducing defects in Chilean salmon fed higher EPA+DHA diets compared to those fed on industry-standard “minimum” diets. Indeed, EPA and DHA supplied through novel sources such as algal oil may enable the restoration of muscle fatty acid profiles to levels exceeding 10% TFA, which has been associated with improved fillet quality and the maintenance of premium market grades (Santigosa et al., 2023b). Collectively, these results suggest that higher dietary EPA+DHA levels are linked not only to improved production performance but also to enhanced product quality and consistency at harvest.

Taken together, the improvements in survival, feed efficiency, and product quality observed in the present study when salmon are fed higher EPA+DHA diets, have direct implications for both economic performance and environmental sustainability. In commercial salmon production, profitability is driven by the combined effects of biological performance and input costs. Under the modelled scenario, improvements in mortality, eFCR, and harvest quality were associated with a positive ROI across the typical range of nutrient unit costs. This suggests that, under the defined assumptions, novel nutritional strategies targeting higher EPA+DHA levels are economically viable.

In parallel, the increase in dietary EPA+DHA levels evaluated in this study has important implications for environmental sustainability. The shift from marine ingredients to plant-based ingredients in salmon feed have been linked to worsening environmental impacts, highlighting the need to secure nutritional quality of the diets to ensure satisfactory biological performance to offset environmental impact (Kok et al., 2026). In the present study, higher inclusion levels were associated with a modest increase in feed-related carbon footprint (2%). However, the improvements in biological performance observed in fish fed higher EPA+DHA levels were more than sufficient to offset these effects, resulting in a substantial net reduction in the carbon footprint per unit of harvested fish (up to 17%). A similar pattern was observed for marine resource use, where improvements in feed efficiency were associated with a reduction in FFDRoil of approximately 15%, reflecting a reduced dependence on finite forage fish resources. These results highlight that gains in production efficiency play a central role in shaping the overall environmental performance of salmon aquaculture systems. Therefore, achieving higher dietary EPA+DHA levels may require the use of scalable and consistent sources of these nutrients. As global fish oil production remains limited (Zatti et al., 2023), alternative omega-3 sources may provide a practical pathway to support higher inclusion levels while reducing reliance on marine resources and maintaining farmed salmons nutritional value (Sprague et al., 2016; Farris et al., 2024).

Despite the large scale and robustness of the analytical approach applied in the present study, several limitations should be acknowledged. First, the observational nature of the dataset does not allow full causal inference, and residual confounding may remain despite the use of population tracing and IPWRA adjustment methods. Although the modelling framework accounted for multiple production- and stress-related covariates, unmeasured factors associated with management practices, health status, environmental variability, or feed formulation may also have contributed to the observed outcomes. In addition, the analysis was limited to total dietary EPA+DHA levels and did not account for potential changes in the EPA:DHA ratio over time, nor for variation in other nutritional components of the diets, including micronutrients and other fatty acids, known also to influence biological performance and robustness of Atlantic salmon (Santigosa et al., 2023a). Therefore, expanding future datasets with additional nutritional, environmental, and production-related variables may improve variable isolation and strengthen the interpretation of commercial big data analyses in commercial aquaculture settings. Finally, the study data was derived exclusively from Norwegian sea-cage systems between 2013 and 2023. Consequently, the applicability of these findings to other regions and alternate production systems may be limited due to differences in environmental, operational and regulatory conditions.

Overall, the results of the present study support the interpretation that higher dietary EPA+DHA levels are associated with measurable improvements in biological performance, product quality, and production consistency under commercial conditions. When integrated within a broader production framework, these improvements may contribute to enhanced economic returns and reduced environmental impact, supporting the development of more efficient and resilient salmon aquaculture systems. Therefore, the availability of consistent and scalable omega-3 sources, including algal oil, may represent an important enabling factor for the practical implementation of better nutrition strategies at commercial scale.

5 Conclusion

The results of the present large-scale observational study indicate that higher dietary EPA+DHA levels (>9%) are associated with improved productivity in Atlantic salmon farming in Norway, including reductions in mortality and eFCR, as well as improvements in harvest quality. These performance gains are accompanied by reduced variability, suggesting enhanced predictability under heterogeneous commercial production conditions. Modelled scenario analyses further suggest that such improvements may translate into reduced environmental impacts, including lower carbon and marine footprints, and positive economic returns, although these outcomes depend on underlying assumptions related to production systems and market conditions. Therefore, scalable and consistent sources of EPA and DHA, such as algal oil, provide a practical pathway to achieve and sustain higher dietary inclusion levels in aquafeeds. By enabling the implementation of enhanced nutritional strategies, emerging omega-3 sources may support the translation of nutritional improvements into measurable commercial and environmental benefits. Overall, these findings highlight the role of dietary EPA and DHA as an important factor in improving the performance, predictability, sustainability and profitability of modern salmon aquaculture systems.

Data availability statement

The datasets presented in this article are not readily available because raw data from farmers cannot be shared. Requests to access the datasets should be directed to Anthony Chen, tony@manolinaqua.com.

Ethics statement

Ethical approval was not required for the study involving animals in accordance with the local legislation and institutional

requirements due to the retrospective nature of the study, which used an existing commercial dataset.

Author contributions

IC: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. SA: Data curation, Formal analysis, Writing – review & editing. YL: Conceptualization, Formal analysis, Writing – review & editing. AC: Data curation, Formal analysis, Methodology, Writing – review & editing. JC: Data curation, Formal analysis, Methodology, Writing – review & editing. ES: Supervision, Validation, Writing – review & editing.

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Conflict of interest

IC, SA and YL are employed by Veramaris; ES is employed by dsm-firmenich; AC and JC are co-founders of Manolin. This study received funding from Veramaris. The funder had the following involvement with the study: the study design, collection, analysis, interpretation of data, the writing of this article and the decision to submit it for publication.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2026.1924168/full#supplementary-material

References

Aas, T. S., Ytrestøyl, T., and Åsgård, T. (2019). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2016. *Aquac. Rep.* 15, 100216. doi: 10.1016/j.aqrep.2019.100216

Aas, T. S., Åsgård, T., and Ytrestøyl, T. (2022). Utilization of feed resources in the production of Atlantic salmon (Salmo salar) in Norway: An update for 2020. *Aquacult. Rep.* 26, 101316. doi: 10.1016/j.aqrep.2022.101316

Albrektsen, S., Kortet, R., Skov, P. V., Ytteborg, E., Gitlesen, S., Kleinegris, D., et al. (2022). Future feed resources in sustainable salmonid production: A review. *Rev. Aquac.* 14, 1790–1812. doi: 10.1111/raq.12673

Bernasconi, A. A., Wiest, M. M., Lavie, C. J., Milani, R. V., and Laukkanen, J. A. (2021). Effect of omega-3 dosage on cardiovascular outcomes: An updated meta-analysis and meta-regression of interventional trials. *Mayo Clin. Proc.* 96, 304–313. doi: 10.1016/j.mayocp.2020.08.034

Bou, M., Berge, G. M., Baeverfjord, G., Sigholt, T., Østbye, T.-K., Romarheim, O. H., et al. (2017). Requirements of n-3 very long-chain PUFA in Atlantic salmon (Salmo salar L): effects of different dietary levels of EPA and DHA on fish performance and tissue composition and integrity. *Br. J. Nutr.* 117, 30–47. doi: 10.1017/S0007114516004396

Calder, P. C. (2017). Omega-3 fatty acids and inflammatory processes: from molecules to man. *Biochem. Soc Trans.* 45, 1105–1115. doi: 10.1042/bst20160474

Carr, I., Glencross, B., and Santigosa, E. (2023). The importance of essential fatty acids and their ratios in aquafeeds to enhance salmonid production, welfare, and human health. *Front. Anim. Sci.* 4. doi: 10.3389/fanim.2023.1147081

Carr, I., Santigosa, E., Chen, T., and Costantino, J. (2024). Optimum eicosapentaenoic acid + docosahexaenoic acid levels for farmed Atlantic salmon: closing the gap between science and commercial practice. *Front. Mar. Sci.* 11. doi: 10.3389/fmars.2024.1379066

FAO (2026). *The State of World Fisheries and Aquaculture 2026 – Blue Transformation: Turning Vision Into Impact* (Rome, Italy: Food and Agriculture Organisation of the United Nations). doi: 10.4060/cd8357en

Farris, N. W., Willora, F. P., Blaauw, D. H., Gupta, S., Santigosa, E., Carr, I., et al. (2024). Progressive substitution of fish oil with Schizochytrium-derived algal oil in the diet of Atlantic salmon (Salmo salar) parr subjected to winter signal period. *Aquac. Rep.* 36, 102130. doi: 10.1016/j.aqrep.2024.102130

Funk, M. J., Westreich, D., Wiesen, C., Stürmer, T., Brookhart, M. A., and Davidian, M. (2011). Doubly robust estimation of causal effects. *Am. J. Epidemiol.* 173, 761–767. doi: 10.1093/aje/kwq439

Glencross, B., Ling, X., Gatlin, D., Kaushik, S., Øverland, M., Newton, R., et al. (2024). A SWOT analysis of the use of marine, grain, terrestrial-animal and novel protein ingredients in aquaculture feeds. *Rev. Fish. Sci. Aquac.* 32, 1–39. doi: 10.1080/23308249.2024.2315049

Goglio, P., Van Den Burg, S., Kousoulaki, K., Skirtun, M., Espmark, Å.M., Kettunen, A. H., et al. (2022). The environmental impact of partial substitution of fish-based feed with algae- and insect-based feed in salmon farming. *Sustainability* 14, 12650. doi: 10.3390/su141912650

Horn, S. S., Sonesson, A. K., Krasnov, A., Moghadam, H., Hillestad, B., Meuwissen, T. H. E., et al. (2019). Individual differences in EPA and DHA content of Atlantic salmon are associated with gene expression of key metabolic processes. *Sci. Rep.* 9, 3889. doi: 10.1038/s41598-019-40391-2

Kok, B., Malcorps, W., Santos, M. J., Newton, R. W., Harmsen, R., and Little, D. C. (2026). Sustainable aquafeed? The devil is in the detail. *J. Clean. Prod.* 546, 147666. doi: 10.1016/j.jclepro.2026.147666

Løvmo, S. D., Whatmore, P., Sundh, H., Sigholt, T., Madaro, A., Bardal, T., et al. (2021). Effects of Atlantic salmon (Salmo salar) fed low- and high HUFA diets on growth and midgut intestinal health. *Aquaculture* 539, 736653. doi: 10.1016/j.aquaculture.2021.736653

Lutfi, E., Berge, G., Baeverfjord, G., Sigholt, T., Bou, M., Larsson, T., et al. (2022). Increasing dietary levels of the omega-3 long-chain polyunsaturated fatty acids, EPA and DHA, improves the growth, welfare, robustness, and fillet quality of Atlantic salmon in sea cages. *Br. J. Nutr.* 129, 10–28. doi: 10.1017/S0007114522000642

Martins, B. P., Bandarra, N. M., and Figueiredo-Braga, M. (2020). The role of marine omega-3 in human neurodevelopment, including Autism Spectrum Disorders and Attention-Deficit/Hyperactivity Disorder - a review. *Crit. Rev. Food Sci. Nutr.* 60, 1431–1446. doi: 10.1080/10408398.2019.1573800

Moldal, T., Wiik-Nielse, J., Silva De Oliviera, V., Svendsen, J., Sommerset, I., and Haukaas, A. (n.d). *Norwegian Fish Health Report 2024*. Available online at: https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2025/norwegian-fish-health-report-2024 (Accessed June 15, 2026).

Mueller, J., Pauly, M., Molkentin, J., Ostermeyer, U., van Muilekom, D. R., Rebl, A., et al. (2023). Microalgae as functional feed for Atlantic salmon: effects on growth, health, immunity, muscle fatty acid and pigment deposition. *Front. Mar. Sci.* 10. doi: 10.3389/fmars.2023.1273614

Neethirajan, S. (2020). The role of sensors, big data and machine learning in modern animal farming. *Sens. BioSensing. Res.* 29, 100367. doi: 10.1016/j.sbsr.2020.100367

Nichols, P. D., Glencross, B., Petrie, J. R., and Singh, S. P. (2014). Readily available sources of long-chain omega-3 oils: is farmed Australian seafood a better source of the good oil than wild-caught seafood? *Nutrients* 6, 1063–1079. doi: 10.3390/nu6031063

Oliver, L., Dietrich, T., Marañón, I., Villarán, M. C., and Barrio, R. J. (2020). Producing Omega-3 polyunsaturated fatty acids: A review of sustainable sources and future trends for the EPA and DHA market. *Resources* 9, 148. doi: 10.3390/resources9120148

Ortega-Gómez, A., Perretti, M., and Soehnlein, O. (2013). Resolution of inflammation: an integrated view. *EMBO Mol. Med.* 5, 661–674. doi: 10.1002/emmm.201202382

Punia, S., Sandhu, K. S., Siroha, A. K., and Dhull, S. B. (2019). Omega 3-metabolism, absorption, bioavailability and health benefits–A review. *PharmaNutrition* 10, 100162. doi: 10.1016/j.phanu.2019.100162

Rosenbaum, P. R., and Rubin, D. B. (1983). The central role of the propensity score in observational studies for causal effects. *Biometrika* 70, 41. doi: 10.2307/2335942

Ruyter, B., Bou, M., Berge, G. M., Mørkøre, T., Sissener, N. H., Sanden, M., et al. (2022). A dose-response study with omega-3 rich canola oil as a novel source of docosahexaenoic acid (DHA) in feed for Atlantic salmon (Salmo salar) in seawater; effects on performance, tissue fatty acid composition, and fillet quality. *Aquaculture* 561, 738733. doi: 10.1016/j.aquaculture.2022.738733

Saini, R. K., and Keum, Y.-S. (2018). Omega-3 and omega-6 polyunsaturated fatty acids: Dietary sources, metabolism, and significance—A review. *Life Sci.* 203, 255–267. doi: 10.1016/j.lfs.2018.04.049

Samuelsen, T. A., Kousoulaki, K., and Bogevik, A. S. (2024). Microalgae suspension as a source of n-3 long-chain PUFA in feed for Atlantic Salmon (Salmo salar L) – Technical constraints and nutritional quality. *Aquaculture* 581, 740459. doi: 10.1016/j.aquaculture.2023.740459

Santigosa, E., Olsen, R. E., Madaro, A., Søfteland, L., and Carr, I. (2023a). The impact of varying EPA:DHA ratio on Atlantic salmon health and welfare. *Aquaculture* 576. doi: 10.1016/j.aquaculture.2023.739868

Santigosa, E., Olsen, R. E., Madaro, A., Søfteland, L., and Carr, I. (2023b). Algal oil gives control of long-chain omega-3 levels in full-cycle production of Atlantic salmon, without detriment to zootechnical performance and sensory characteristics. *J. World Aquac. Soc* 54, 861–881. doi: 10.1111/jwas.12947

Selvam, C., Philip, A. J. P., Lutfi, E., Sigholt, T., Norberg, B., Bæverfjord, G., et al. (2022). Long-term feeding of Atlantic salmon with varying levels of dietary EPA + DHA alters the mineral status but does not affect the stress responses after mechanical delousing stress. *Br. J. Nutr.* 128, 2291–2307. doi: 10.1017/S0007114522000514

Simpson, E. H. (1951). The interpretation of interaction in contingency tables. *J. R. Stat. Soc Ser. B. Stat. Methodol.* 13, 238–241. doi: 10.1111/j.2517-6161.1951.tb00088.x

Sissener, N. H., Waagbø, R., Rosenlund, G., Tvenning, L., Susort, S., Lea, T. B., et al. (2016). Reduced n-3 long chain fatty acid levels in feed for Atlantic salmon (Salmo salar L.) do not reduce growth, robustness or product quality through an entire full scale commercial production cycle in seawater. *Aquaculture* 464, 236–245. doi: 10.1016/j.aquaculture.2016.06.034

Sprague, M., Dick, J. R., and Tocher, D. R. (2016). Impact of sustainable feeds on omega-3 long-chain fatty acid levels in farmed Atlantic salmon 2006–2015. *Sci. Rep.* 6, 1–9. doi: 10.1038/srep21892

Sprague, M., Fawcett, S., Betancor, M. B., Struthers, W., and Tocher, D. R. (2020). Variation in the nutritional composition of farmed Atlantic salmon (Salmo salar L.) fillets with emphasis on EPA and DHA contents. *J. Food. Compost. Anal.* 94, 103618. doi: 10.1016/j.jfca.2020.103618

Tao, Q., Ding, H., Wang, H., and Cui, X. (2021). Application research: Big data in food industry. *Foods* 10, 2203. doi: 10.3390/foods10092203

Tocher, D. R. (2015). Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective. *Aquaculture* 449, 94–107. doi: 10.1016/j.aquaculture.2015.01.010

Zatti, K. M., Ceballos, M. J., Vega, V. V., and Denstadli, V. (2023). Full replacement of fish oil with algae oil in farmed Atlantic salmon (Salmo salar) – Debottlenecking omega 3. *Aquaculture* 574, 739653. doi: 10.1016/j.aquaculture.2023.739653