

# Sunstone Institute

# Nutrient Analysis Report

*Assessing Nutrient Discharges from  
Norwegian Aquaculture into Coastal Waters*

# Abstract

This report presents a comprehensive quantitative analysis of nutrient waste discharge from Norwegian aquaculture operations for the period 2020–2025. The report focuses on Atlantic salmon and rainbow trout farming, which represent the dominant species in Norwegian fish farming.

Using the well-known mass balance equations aligned with the TEOTIL3 model developed by the Norwegian Institute for Water Research (NIVA), we quantitatively estimated annual fluxes of nitrogen (N), phosphorus (P), and organic carbon (OC). These estimations were based on parameters such as feed intake, fish biomass production, biomass change, and mortality rates.

In 2025, Norwegian aquaculture released 75,382 tonnes of nitrogen, 13,111 tonnes of phosphorus, and 359,926 tonnes of organic carbon into coastal waters. These nutrient inputs are equivalent to untreated sewage from 17.21 million people (nitrogen), 19.96 million people (phosphorus), and 29.58 million people (organic carbon).

All calculations were validated against the TEOTIL3 reference model for the available years (2020–2023), with results within  $\pm 3\%$  of the reference, thereby confirming the accuracy of the methodology.

**Keywords:** aquaculture; salmon farming; nitrogen; phosphorus; organic carbon; nutrient discharge; eutrophication; mass balance; environmental impact

# Table of Contents

1. Introduction.....	7
1.1. Norwegian Aquaculture Industry.....	7
1.2. Nutrient discharges.....	8
2. Project Scope and Objectives.....	9
2.1. Primary Objectives.....	9
2.2. Scope Boundaries.....	9
3. Data Sources.....	10
3.1. Feed Consumption Data.....	10
3.2. Biomass Data.....	11
3.3. Slaughter Data.....	11
3.4. Mortality Data.....	12
4. Methodology.....	12
4.1. Mass Balance Framework.....	12
4.2. Key Coefficients and Parameters.....	13
4.3. Feed Consumption Calculations.....	14
4.4. Slaughter Calculations.....	14
4.5. Biomass Change Calculations.....	15
4.6. Mortality Conversions.....	15
4.6.1. Mortality Weight Estimates.....	16
4.6.2. Mortality Biomass Conversion.....	16
4.6.3. Species-Level Assumptions.....	17
4.6.4. Methodology Considerations.....	17
4.7. Mortality Sensitivity Analysis.....	18
4.7.1. Mortality Weight Ranges.....	18
4.7.2. Scenario Definition.....	19
4.7.3. Impact on Nutrient Waste.....	19
4.8. Population Equivalence Methodology.....	20

- 4.9. Results Quality Review..... 23
- 5. Results and Findings..... 24
  - 5.1. Annual Nutrient Discharge..... 24
  - 5.2. Temporal Trends (2020–2025)..... 25
  - 5.3. Feed Efficiency and Retention..... 25
    - 5.3.1. Nutrient Retention Patterns..... 25
    - 5.3.2. Temporal Improvements..... 26
  - 5.4. Population Equivalence..... 26
- 6. Validation..... 28
  - 6.1. Validation Methodology..... 28
  - 6.2. TEOTIL3 Model Comparison..... 28
  - 6.3. Validation Results..... 29
- 7. Discussion..... 30
  - 7.1. Environmental Implications..... 30
  - 7.2. Comparison with Reference Models..... 31
  - 7.3. Uncertainties and Limitations..... 31
  - 7.4. Implications for Aquaculture Management..... 32
- 8. Conclusions..... 33
- Acknowledgments..... 34
- References..... 35

# List of Figures

Figure 1. Impact of open-net cage farms at sea.....8

Figure 2. Annual distribution of the retained and wasted fractions of N and P (2020–2025)..... 26

Figure 3. Nutrient discharge expressed as PE (2025)..... 27

# List of Tables

Table 1. Primary data sources.....	10
Table 2. Key coefficients and parameters.....	14
Table 3. Organic carbon waste factor.....	14
Table 4. Mortality weight estimates by production phase.....	16
Table 5. Sea-phase mortality weight groups (kg).....	18
Table 6. Hatchery-phase mortality weight groups (g).....	18
Table 7. Mortality weight estimates and uncertainty range.....	19
Table 8. Nitrogen waste under different mortality weight assumptions (2025).....	20
Table 9. Phosphorus waste under different mortality weight assumptions (2025).....	20
Table 10. Average per-capita daily contributions to domestic wastewater in different countries.....	21
Table 11. Nutrient discharge factors and annual outputs.....	22
Table 12. External experts panel for the nutrient analysis project.....	23
Table 13. Nutrient Analysis team (excluding experts).....	24
Table 14. Annual nutrient discharge.....	24
Table 15. Feed efficiency metrics.....	25
Table 16. Aquaculture waste in Population Equivalents, in millions of people, per year.....	27
Table 17. Model validation against TEOTIL3 (2020–2023).....	29

# 1. Introduction

The Norwegian aquaculture sector is a globally significant industry that contributes substantially to economic growth in coastal communities. However, the rapid expansion and intensification of salmon farming in Norwegian coastal waters have raised significant concerns about the effects on coastal water quality and marine biodiversity. This report quantifies nutrient pollution, focusing on nitrogen (N), phosphorus (P), and organic carbon (OC) inputs from aquaculture operations. Understanding and quantifying these nutrient discharges is essential for assessing the environmental impacts of the open-net cages of Norwegian fish farms.

## 1.1. Norwegian Aquaculture Industry

Norway initiated Atlantic salmon farming in the 1970s and has since become the world's largest producer, followed by Chile, the United Kingdom, Canada, and the Faroe Islands (Pandey *et al.*, 2023). In 2022, Norway accounted for 52.77% of global Atlantic salmon production (FAO, 2023) and maintained approximately 989 active farms distributed across its coastal regions. By 2025, the number of active farms had increased to 995 (Fiskeridirektoratet, 2026), with MOWI as the largest commercial producer in this sector (Pandey *et al.*, 2023). In the broader context of global aquaculture, salmon and trout farming accounts for approximately 3% of total fish farming production (FAO, 2025).

Although the industry makes a substantial contribution to Norwegian national economic growth, the sector faces escalating environmental and animal welfare challenges that require quantification and management (Nærings- og fiskeridepartementet, 2025). Recent health data highlight these pressures: in 2024, 15.4% of salmon produced died, of which 32.9% was due to infectious diseases and 26.6% to trauma (Veterinærinstituttet, 2026). The Norwegian Ministry of Trade, Industry and Fisheries considers these mortality rates unacceptably high and identifies opportunities for improvement through improved management practices (Nærings- og fiskeridepartementet, 2025). Concurrently, monthly and annual increases in nutrient inputs have been observed, correlated with rising production, particularly during the August-to-October period, when waste emission levels are elevated (Wang & Olsen, 2023). Notably, these nutrient inputs are predominantly sourced from imported feed, with a high proportion originating overseas (Skretting, 2023a; Skretting, 2023b).

These nutrients ultimately contribute to pollution, as salmon production generates various forms of ocean pollution, including fish mortality events, residual feed, excretory waste, chemicals, and pharmaceuticals (Nærings- og fiskeridepartementet, 2025). Stakeholders recognise these issues and have identified environmental priorities, with farm mortality rates regarded as an animal welfare concern and nutrient and organic emissions acknowledged as key sources of pollution (Haugen & Olaussen, 2025). Concurrently, there is substantial public support for initiatives to reduce environmental impacts and enhance the ecological and welfare conditions of wild salmon

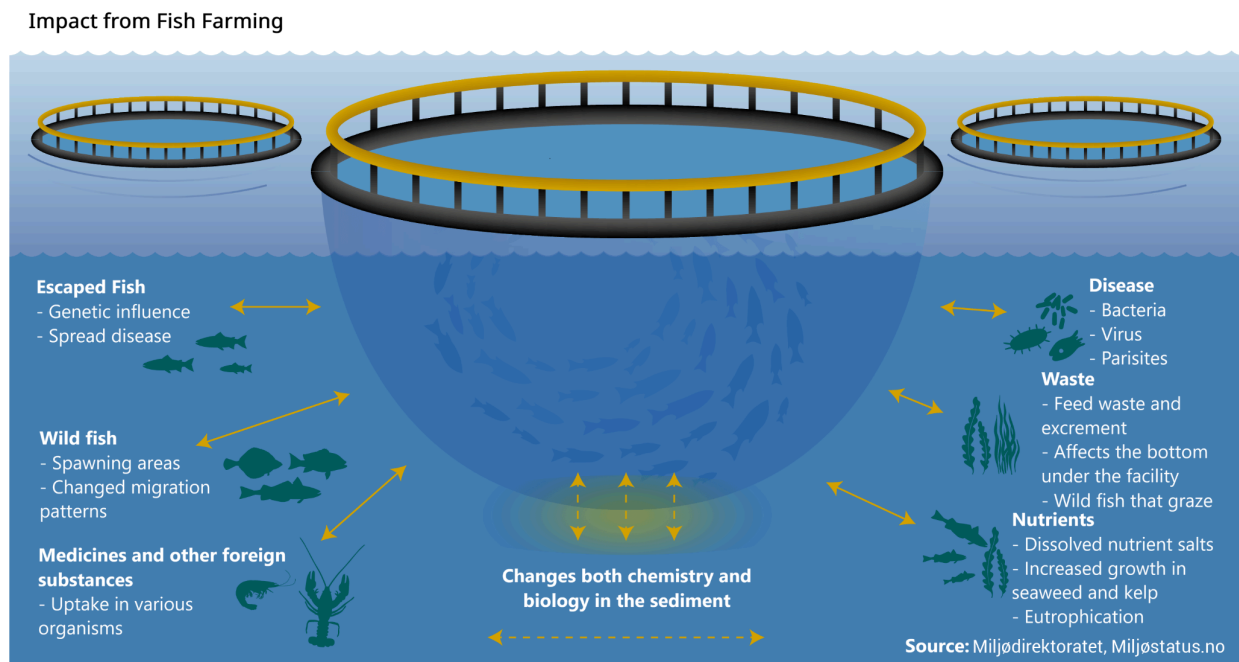
populations (Berrios *et al.*, 2026). These populations have been adversely affected by sea lice infestations originating from salmon farms, among other stressors (Larsen *et al.*, 2024; Krkosek *et al.*, 2024).

Given the multifaceted nature of aquaculture pollution, this report will primarily focus on nutrient discharges in Norwegian coastal waters.

## 1.2. Nutrient discharges

As previously indicated, nutrient discharges from open-net cages constitute a pollution source in the aquaculture sector, affecting water quality and ecosystem health (Amirkolaie, 2011). These nutrient inputs are primarily derived from feed supplementation, with subsequent release into the aquatic environment facilitated by biological and mechanical processes, including fish excretion, gill filtration, and dispersal of residual feed waste (Ahmad *et al.*, 2022). **Figure 1** shows how the different interactions and pathways in these nutrient flows work together.

**Figure 1.** Impact of open-net cage farms at sea.



Source: Miljødirektoratet, Miljøstatus (Translated)

When these nutrients remain untreated, their excessive release modifies the coastal water environment. This increase in nutrient levels triggers eutrophication, leading to hypoxic conditions and the proliferation of algae (algal blooms) that threaten marine ecosystems by causing species declines and habitat destruction (Dai *et al.*, 2023). At the species level, Haugland *et al.* (2021)

demonstrated that fish farm effluent significantly alters the epiphytic community structure on *Laminaria hyperborea*, particularly under high effluent loads. Their analysis showed a shift in species composition, with bryozoans becoming dominant while sensitive red algae, such as *Palmaria palmata* and *Delesseria sanguinea*, are suppressed or locally extinct. Staalstrøm *et al.* (2025) further found that increased nutrient input from aquaculture contributes to approximately two-thirds of the observed oxygen decrease in deep waters of the fjord zones, establishing a direct causal link between farm discharges and benthic hypoxia.

Preliminary observations by NIVA researchers indicate reduced ecological quality along extensive stretches of the Norwegian coastline (H. Christie, February 4, 2026; see **Table 12**). While the relationships linking nutrient inputs to specific ecological responses require further investigation, quantifying aquaculture nutrient discharges provides a baseline for a detailed future assessment of fish farm-coastal ecosystem relationships.

To establish this baseline, the primary nutrients analysed in this report are organic carbon, nitrogen, and phosphorus. These three forms encompass the primary nutrient components released from aquaculture operations and represent the most significant contributors to coastal eutrophication and oxygen depletion.

## 2. Project Scope and Objectives

### 2.1. Primary Objectives

The primary objective of developing this model was to quantify the discharge of organic carbon, nitrogen, and phosphorus from Norwegian aquaculture into coastal waters. It aimed to develop a simplified, validated mass balance model that accurately reproduces reference calculations from TEOTIL3 (Sample *et al.*, 2024) with a deviation of no more than  $\pm 3\%$ , using fewer input assumptions regarding nutrient partitioning. Additionally, the model aimed to contextualise nutrient loads by calculating population equivalents, providing a standardised metric for assessing environmental impact relative to traditional pollution sources. Finally, it sought to document the methodology and assumptions transparently to facilitate reproducibility, independent verification, and future refinement of the model.

### 2.2. Scope Boundaries

The following boundaries define this study's scope:

**Species:** Atlantic Salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*)

**Geographic coverage:** All Norwegian Coastal regions (national-level aggregate)

**Time period:** 2020–2025, inclusive.

**Production phases:** Sea-phase and hatchery-phase

**Nutrients analysed:** Organic Carbon (OC), Nitrogen (N), Phosphorus (P).

The analysis does not include particulate organic carbon speciation, such as dissolved versus particulate fractions, regional spatial variation in environmental impact, species-specific differences in waste production (since both salmon and trout are analysed using unified coefficients), seasonal variation beyond annual aggregation, or indirect nutrient loading through escapes or deposition on wild stock habitats.

### 3. Data Sources

The model relies on four primary datasets from authoritative Norwegian sources, each serving a distinct role in the mass balance calculations. All data are publicly available, represent official statistics, and are subject to mandatory reporting requirements for licensed aquaculture facilities. The four datasets and their attributes are summarised in **Table 1**.

Data were obtained from Fiskeridirektoratet (Norwegian Directorate of Fisheries) and Veterinærinstituttet (Norwegian Veterinary Institute) through their online statistical portals. Quality assurance procedures included cross-referencing annual totals between sources, checking for missing values or anomalies, and verifying unit conversions. Monthly data were aggregated into annual totals where applicable to align with the analysis period. All data processing was performed using Python 3.12 or higher, with source code provided to ensure reproducibility.

**Table 1.** Primary data sources.

Dataset	Source	Coverage	Frequency
Feed Consumption	Fiskeridirektoratet	2005–2025	Monthly/Annual
Biomass Stock	Fiskeridirektoratet	2019–2025	Monthly
Slaughter	Fiskeridirektoratet	2018–2025	Monthly/Annual
Mortality	Veterinærinstituttet	2020–2025	Annual

#### 3.1. Feed Consumption Data

Feed consumption serves as the primary input to mass balance calculations, representing the total nutrient load entering the open-net cage. This dataset quantifies the mass of commercial feed delivered to fish farms. Feed consumption is the starting point for all nutrient flow calculations, as it defines the maximum quantity of nitrogen, phosphorus, and carbon available for retention in fish

biomass or release as waste.

Data is reported monthly by production companies to Fiskeridirektoratet as part of mandatory reporting obligations under Norwegian aquaculture regulations. The dataset covers the period from 2005 to the present. For this analysis, data collected between 2020 and 2025 were extracted and aggregated annually. However, the primary limitation of this dataset is that it does not distinguish between feed consumed by fish and feed lost to the environment, nor between phases (hatchery and sea). The TEOTIL3 waste factor (see methodology: Key Coefficients and Parameters) accounts for this distinction by estimating that approximately 3% of the feed is not consumed and is directly converted to particulate waste.

### *3.2. Biomass Data*

Biomass stock data quantifies the total standing stock of live fish within sea-phase production facilities at the end of each month, measured in tonnes of live weight. This dataset is essential for calculating the net change in fish biomass over time, which represents nutrients retained in fish that remain in the system rather than being harvested or lost to mortality.

Data is reported monthly to Fiskeridirektoratet by all licensed sea-phase facilities, categorised by species (Atlantic salmon and rainbow trout) and geographic region. The dataset provides comprehensive coverage from 2019 to 2025, with monthly snapshots.

Despite this comprehensive coverage, an important limitation of this dataset is that it captures only sea-phase biomass. Hatchery-phase biomass is not included in these measurements.

### *3.3. Slaughter Data*

Slaughter data quantifies the biomass of fish removed from production through commercial harvesting operations, measured in tonnes of whole-fish weight. This dataset represents the primary pathway by which nutrients exit the aquaculture system, as harvested fish retain the nitrogen and phosphorus incorporated into their tissues during the growth period.

The dataset covers 2018 to 2025, with both monthly and annual aggregations available. For this analysis, annual totals were used to align with the temporal resolution of mortality data and to ensure consistency across the mass balance framework.

Slaughter values are recorded as whole fish weight at the point of harvest, prior to processing or value-added operations. This measurement approach ensures consistency with biomass stock measurements and feed conversion calculations.

While measurement methods are standardised, slaughter timing may vary seasonally in response to market demand and to optimise fish size. However, annual aggregation captures total nutrient export regardless of its temporal distribution within the year.

### 3.4. Mortality Data

Mortality data quantifies fish losses attributable to disease, environmental stressors, handling trauma, and other causes throughout the production cycle. These losses represent a significant nutrient retention within the system.

Data are compiled annually by Veterinærinstituttet through the national fish health surveillance program and published in the Fiskehelse rapporten (Fish Health Report). Feed, biomass, and slaughter data are reported in mass units. Mortality statistics are reported as the number of individual fish that died, necessitating conversion to mass units for inclusion in nutrient calculations.

The dataset distinguishes between two production phases: the sea and hatchery phases. Fish mortality occurs across a wide size range, from first-feeding fry weighing less than 1 gram to market-sized fish weighing more than 5 kilograms. Phase-specific mortality counts are categorised separately for Atlantic salmon and rainbow trout.

## 4. Methodology

### 4.1. Mass Balance Framework

This study employs a mass balance approach to quantify nutrient waste from Norwegian salmon and rainbow trout aquaculture, following the fundamental principle established by Wang *et al.* (2012):

$$If = Af + Ff = Gf + Ef + Ff$$

where  $If$  is feed input,  $Af$  is assimilated feed,  $Ff$  is defecation,  $Gf$  is growth (retention in biomass), and  $Ef$  is excretion. This equation can be rearranged to:

$$Waste = Feed - Retention$$

Wang *et al.* (2012) further subdivided waste into six components. However, our implementation calculates total nutrient waste as an aggregate term, without separating waste components:

$$N_{waste} = N_{feed} - N_{slaughter} - N_{biomass} - N_{mortality}$$

$$P_{waste} = P_{feed} - P_{slaughter} - P_{biomass} - P_{mortality}$$

$$OC_{waste} = Feed_{total} \times C_{feed} \times WasteFactor$$

This approach requires fewer assumptions about assimilation efficiencies and particle dissolution rates. The trade-off is that our model does not distinguish between dissolved and particulate waste fractions, which Wang *et al.* (2012) found to be approximately 45% DIN and 15% PON for nitrogen, and 18% DIP and 44% POP for phosphorus. Thus, our reported  $N_{waste}$  and  $P_{waste}$  represent the combined total of all inorganic and organic forms released to the environment. The variables in each formula are described in subsequent sections.

For organic carbon, we apply the empirical waste factor (0.321) from TEOTIL3, which implicitly accounts for the partitioning between respired CO<sub>2</sub> (approximately 48% of feed carbon according to Wang *et al.*, 2012), particulate organic carbon, and dissolved organic carbon. This factor represents the proportion of feed carbon released as solid and dissolved organic waste, excluding respiratory CO<sub>2</sub> losses.

## 4.2. Key Coefficients and Parameters

The mass balance calculations rely on fixed nutrient composition coefficients for feed and fish tissue. These coefficients represent average values derived from the TEOTIL3 model (Sample *et al.*, 2024). All coefficients are expressed as mass percentages. Feed coefficients define the nutrient content of commercial aquaculture feed delivered to farms. The feed's nitrogen content of 5.84% indicates its protein levels, while the phosphorus content of 0.96% derives primarily from fishmeal and bone meal components. Additionally, the 49% carbon content represents the organic fraction of feed ingredients, including lipids, proteins, and carbohydrates.

Fish tissue coefficients define the nutrient content retained in fish biomass at harvest or death. These values (2.96% nitrogen, 0.45% phosphorus) were sourced from TEOTIL3. The lower nitrogen and phosphorus concentrations in fish tissue compared to feed reflect the inefficiency of nutrient transfer in aquaculture systems. Only a fraction of nutrients consumed is retained in harvestable biomass, with the remainder released as metabolic waste or unconsumed feed. The difference between feed input and tissue retention underpins waste calculations. These coefficients, presented in **Table 2**, remain constant across all years (2020–2025).

The waste factor differentiates the calculation approach for organic carbon from that of nitrogen and phosphorus. While N (Nitrogen) and P (Phosphorus) waste are calculated via mass balance (feed input minus all retention pathways), organic carbon uses a fixed empirical waste factor of 0.321 (32.1%), as previously mentioned. This factor represents the fraction of feed carbon deposited to the environment as particulate organic matter. The value derives from two loss pathways (Sample *et al.*, 2024):

- Faecal production ( $0.97 \times 0.30 = 0.291$ , representing 30% of consumed feed becoming faeces)
- Uneaten feed pellets (0.03, representing 3% of the feed that sinks unconsumed).

This approach, adapted from the TEOTIL3 model, accounts for the distinct pathways of carbon relative to N and P in aquaculture systems. While nitrogen and phosphorus are released as both

dissolved metabolic waste and particulate matter, the carbon waste factor captures solid organic carbon deposited in the benthic environment. The resulting factor is presented in **Table 3**.

**Table 2.** Key coefficients and parameters.

Component	Nitrogen	Phosphorus	Carbon
Feed	5.84 %	0.96 %	49 %
Fish Tissue	2.96 %	0.45 %	-

**Table 3.** Organic carbon waste factor.

Component	Value
Organic Carbon Waste Factor	32.1%

### 4.3. Feed Consumption Calculations

Feed consumption represents the primary nutrient input to the aquaculture system. Total feed mass (reported in tonnes) is converted to nutrient quantities by multiplying by the respective feed composition coefficients. These calculations establish the maximum nutrient load available for either retention in fish biomass or release as waste.

$$N_{feed} = Feed_{total} \times N_{feed}$$

$$P_{feed} = Feed_{total} \times P_{feed}$$

where  $Feed_{total}$  is the annual feed consumption (tonnes),  $N_{feed} = 0.0584$  (5.84%), and  $P_{feed} = 0.0096$  (0.96%), as previously demonstrated in **Table 2**.

### 4.4. Slaughter Calculations

The nutrient content of slaughtered fish is calculated by multiplying total slaughter biomass (tonnes) by fish tissue composition coefficients. These nutrients are retained in harvested fish rather than released into the environment, thereby reducing the waste discharge calculation.

$$N_{slaughter} = Slaughter_{total} \times N_{fish\_tissue}$$

$$P_{slaughter} = Slaughter_{total} \times P_{fish\_tissue}$$

where  $Slaughter_{total}$  is the annual slaughter biomass (tonnes),  $N_{fish\_tissue} = 0.0296$  (2.96%), and  $P_{fish\_tissue} = 0.0045$  (0.45%), as previously shown in **Table 2**.

## 4.5. Biomass Change Calculations

For mass balance calculations, December biomass values from consecutive years are used to estimate annual biomass change. The calculation

$$BiomassChange = Biomass_{Dec(year)} - Biomass_{Dec(year-1)}$$

quantifies the net accumulation or depletion of standing stock in tonnes. A positive biomass change indicates that more fish biomass was added to the system than was removed through slaughter and mortality, representing nutrient retention in live fish. Conversely, a negative change in biomass indicates a net reduction in stock.

December values were selected to maintain consistent annual timing and represent the full production cycle.

$$N_{biomass} = BiomassChange \times N_{fish\_tissue}$$

$$P_{biomass} = BiomassChange \times P_{fish\_tissue}$$

where  $N_{fish\_tissue}$  is the nitrogen content coefficient, and  $P_{fish\_tissue}$  is the phosphorus content coefficient. These coefficients are shown in **Table 2**.

## 4.6. Mortality Conversions

In the mass balance framework, mortality represents a nutrient retention pathway: nutrients incorporated into fish tissue that die remain within the system but do not contribute to commercial harvest. Accurate quantification of mortality distinguishes nutrients retained in productive biomass (slaughter) from those retained in dead fish, which are removed through carcass disposal but still represent nutrients that must be accounted for in the system balance.

While the Fish Health Report (Veterinærinstituttet, 2026) also provides mortality as a cumulative percentage of total stocked biomass, we opted to use the absolute number of individual fish deaths for biomass conversion. Using the absolute count of dead fish provides a more direct and transparent pathway to biomass estimation, reducing the propagation of potential inconsistencies in

stocking data.

## 4.6.1. Mortality Weight Estimates

Average weight at death was estimated separately for sea-phase and hatchery-phase production based on mortality distribution data from Fiskehelse rapporten 2025 (Veterinærinstituttet, 2026). The estimates are summarised in **Table 4**.

**Table 4.** Mortality weight estimates by production phase.

Phase	Weight (kg)
Sea-phase	2.1
Hatchery-phase	0.06

### *Sea-Phase (2.1 kg)*

In the sea-phase, median monthly mortality is elevated in the largest weight class (>3.7 kg) relative to intermediate classes. However, all weight categories display considerable variability, with outliers indicating episodic mortality events across the size distribution. The weight of 2.1 kg is the unweighted average of bin midpoints across the production cycle (see below).

### *Hatchery-Phase (0.06 kg)*

Hatchery-phase mortality spans the weight classes defined in the Fiskehelse rapporten 2025 (Veterinærinstituttet, 2026). Median monthly mortality is highest in the smallest weight class (3–11.9 g) and generally declines with increasing size. The base case estimate of 60 g represents the unweighted average of bin midpoints across all hatchery weight classes.

These estimates were derived by calculating the unweighted average of bin midpoints across all weight classes reported in Fiskehelse rapporten 2025 (Veterinærinstituttet, 2026), Figures 2.4.2 and 2.3.4. For the sea-phase, the average of bin midpoints yielded 2.07 kg, rounded to 2.1 kg. For the hatchery-phase, the average of bin midpoints yielded 59.67 g, rounded to 60 g (0.06 kg).

## 4.6.2. Mortality Biomass Conversion

Mortality data, reported as individual fish counts, are converted to biomass (tonnes) using phase-specific weight (kg) estimates:

$$Mortality_{sea} \text{ (millions kg)} = (salmon_{sea} + trout_{sea}) \times 2.1$$

$$Mortality_{hatchery} \text{ (millions kg)} = (salmon_{hatchery} + trout_{hatchery}) \times 0.06$$

$$Mortality_{total} \text{ (tonnes)} = (Mortality_{sea} + Mortality_{hatchery}) \times 1000$$

where *salmon\_sea* and *trout\_sea* are mortality counts (in millions) for sea-phase production, and *salmon\_hatchery* and *trout\_hatchery* are mortality counts (in millions) for the hatchery-phase. The coefficients of 2.1 and 0.06 are phase-specific average weights (kg) at death. Since mortality counts are in millions, multiplying by a weight in kg yields a result in millions of kg. The factor of 1,000 arises from expressing counts in millions ( $\times 10^6$ ) and converting kilograms to tonnes ( $\div 10^3$ ), i.e.,  $10^6 / 10^3 = 10^3$ . Once the total mortality biomass is established, nutrient content is calculated using the tissue composition coefficients listed in **Table 2**.

$$N_{mortality} = Mortality_{total} \times N_{fish\_tissue}$$

$$P_{mortality} = Mortality_{total} \times P_{fish\_tissue}$$

### 4.6.3. Species-Level Assumptions

The same mortality-weight parameters are applied to both Atlantic salmon and rainbow trout. Two factors justify this simplification:

1. Atlantic salmon accounts for approximately 93% of total mortality events in Norwegian aquaculture. Therefore, the impact of species-specific weight differences is limited on national-scale nutrient accounting.
2. Published mortality data lack sufficient resolution for robust species-specific weight estimation, particularly for rainbow trout, which represents a minor fraction of total production.

### 4.6.4. Methodology Considerations

Mortality weight estimates represent unweighted averages of bin midpoints derived from binned distribution data. The sensitivity analysis (Section below: Mortality Sensitivity Analysis) quantifies the impact of alternative mortality weight assumptions on nutrient waste calculations.

## 4.7. Mortality Sensitivity Analysis

The mortality weight parameters are point estimates derived from percentile-binned mortality distributions in Fiskehelse rapporten 2025 (Veterinærinstituttet, 2026), as previously noted. These estimates represent the bin-midpoint averages from 4.6.1. The heterogeneity in mortality across size classes introduces systematic uncertainty that can be quantified.

To assess the sensitivity of nutrient waste calculations to alternative mortality weight assumptions, we conducted a range-based uncertainty analysis. We employed adjacent bin midpoints to define uncertainty bounds. This approach accounts for asymmetry in the mortality-weight distribution by bracketing the bin-midpoint average with the adjacent lower and upper bins.

### 4.7.1. Mortality Weight Ranges

Mortality distribution data from Fiskehelse rapporten 2025 (Veterinærinstituttet, 2026) provide frequency distributions of mortality rates across discrete weight classes. These figures display mortality rates (%) by weight class over time. Analysis of the previously mentioned figures reveals that monthly mortality rates vary across weight classes, with median values broadly ranging from 0.3–1.4% in the sea-phase and 0.2–0.8% in the hatchery-phase. In the sea-phase, the heaviest weight class (>3.7 kg) consistently shows higher mortality relative to intermediate classes. In the hatchery-phase, the lightest class (3–11.9 g) shows the highest median mortality. These patterns indicate that mortality risk is somewhat elevated at the size extremes, introducing systematic uncertainty in the bin-midpoint average weight assumption that the following sensitivity analysis is designed to address. The weight groups for each phase are shown in **Table 5** (sea-phase) and **Table 6** (hatchery-phase).

**Table 5.** Sea-phase mortality weight groups (kg).

	Sea-phase mortality (kg)
	<0.55
Weight	0.55-1.25
groups	1.25-2.35
	2.35-3.7
	>3.7

**Table 6.** Hatchery-phase mortality weight groups (g).

	Hatchery-phase mortality (g)
	3-11.9
Weight	12-36.2
groups	36.3-68.1
	68.2-115.5
	>115.5

## 4.7.2. Scenario Definition

We defined three estimation scenarios to assess variations in the bin-midpoint averages while acknowledging data limitations:

**Lower bound** (adjacent bin below base case): Assumes the bin-midpoint average is biased toward the smaller fish within the observed distribution, representing a scenario where post-transfer mortality and early-stage losses contribute disproportionately to total mortality biomass. Sea-phase: 0.9 kg (midpoint of 0.55–1.25 kg bin); Hatchery-phase: 24 g (midpoint of 12–36.2 g bin).

**Base case:** Applies previously stated unweighted averaging of bin midpoints across all weight classes. This case represents the central estimate (2.1 kg in the sea phase, 60 g in the hatchery phase) used throughout the main analysis. Sea-phase: 2.1 kg; Hatchery-phase: 60 g (0.06 kg)

**Upper bound** (adjacent bin above base case): Assumes the bin-midpoint average is biased toward larger fish within the observed distribution, representing a scenario where late-stage mortality from chronic disease or environmental stress contributes disproportionately to total mortality biomass. Sea-phase: 3.0 kg (midpoint of 2.35–3.7 kg bin); Hatchery-phase: 92 g (midpoint of 68.2–115.5 g bin).

These three scenarios are summarised in **Table 7**.

**Table 7.** Mortality weight estimates and uncertainty range.

Phase	Lower bound	Base Case	Upper bound
Sea-phase	0.9 kg	2.1 kg	3.0 kg
Hatchery-phase	24 g	60.0 g	92 g

## 4.7.3. Impact on Nutrient Waste

To quantify the propagation of mortality weight uncertainty through the mass balance framework, total nitrogen and phosphorus waste were recalculated for 2025 using the lower-bound and upper-bound mortality weight assumptions while holding all other model parameters constant (feed consumption, slaughter, biomass change, nutrient coefficients). The results for N and P are presented in **Tables 8** and **9**, respectively.

**Table 8.** Nitrogen waste under different mortality weight assumptions (2025).

Scenario	Total N Mortality (tonnes)	Total N Waste (tonnes)	% Waste change from base
Lower bound	1 581	77 495	+2.80
Base Case	3 694	75 382	-
Upper bound	5 286	73 790	-2.11

**Table 9.** Phosphorus waste under different mortality weight assumptions (2025).

Scenario	P Mortality (tonnes)	Total P Waste (tonnes)	% Waste change from base
Lower bound	240	13 433	+2.45
Base Case	562	13 111	-
Upper bound	804	12 869	-1.85

Across the range of mortality weight assumptions defined by adjacent bin midpoints, nitrogen waste varies by +2.80% to -2.11% and phosphorus waste by +2.45% to -1.85% relative to the base case. The inverse relationship between mortality weight and waste output reflects the mass balance structure: larger mortality weights increase nutrient retention, thereby reducing calculated waste. Since mortality accounts for approximately 3% of total feed nutrients, variations in mortality parameters produce proportionally smaller changes in total waste estimates. Additionally, the narrow range of  $\pm 2.80\%$  confirms that total nutrient waste estimates are robust to plausible variations in the mortality weighting assumption, despite the observed concentration of mortality at size extremes.

#### *4.8. Population Equivalence Methodology*

To relate the ecological impact of nutrient pollution from aquaculture on Norwegian coastal waterways, it was necessary to express pollutant loads in a standardised, widely used unit for wastewater regulation and pollution assessment. For this purpose, population equivalence (PE) was used, a metric that converts measured nutrient emissions into the equivalent population whose domestic wastewater would generate the same pollutant load. In this assessment, the population equivalence value was calculated separately for three individual chemical biomarkers: nitrogen, phosphorus, and organic carbon. Nitrogen, phosphorus, and organic carbon were selected as they represent the primary nutrient drivers of eutrophication and organic loading in coastal waters and are consistently reported in Norwegian monitoring frameworks (TEOTIL3). For each biomarker, PE was derived by comparing observed environmental loads to established per-capita emission factors that represent average daily contributions from domestic wastewater. As the analysis focuses on coastal

water pollution in Norway, nationally reported per-capita values from Statistisk Sentralbyrå (SSB) were applied for nitrogen and phosphorus. At the same time, organic carbon conversion factors were taken from the EU Urban Wastewater Treatment Directive.

The EU Urban Wastewater Treatment Directive defines population equivalence as “the organic biodegradable load having a five-day biochemical oxygen demand (BOD<sub>5</sub>) of 60 g of oxygen per day” (European Union, 2004). Under this definition, every 60 g of measured BOD<sub>5</sub> corresponds to the average daily organic load produced by one person. For nitrogen and phosphorus, national reference values published by Statistics Norway are used, which define average per-capita discharges of 12 g of nitrogen and 1.8 g of phosphorus per person per day (Berge & David Rittel, 2025), consistent with the TEOTIL3 model, which applies the same per-capita reference values as documented in their publicly available methodology (Sample *et al.*, 2024).

These values were selected to calculate the population equivalence of pollution in Norwegian coastal waters due to their direct relevance to the study context. The reference values published by the EU and Statistics Norway are internationally comparable and align closely with those reported for countries such as Canada, the United Kingdom, and the United States (**Table 10**).

**Table 10.** Average per-capita daily contributions to domestic wastewater in different countries.

Region	Organic Load (BOD <sub>5</sub> )	Total Nitrogen (N)	Total Phosphorus (P)
Norway <sup>a</sup>	60g	12g	1.8g
United Kingdom	60g <sup>b</sup>	N/A	2.3g <sup>c</sup>
USA	77.1g <sup>d</sup>	11.2g <sup>e</sup>	2.7g <sup>e</sup>
Canada <sup>f</sup>	80g	13g	2.1g

<sup>a</sup>Berge & David Rittel (2025)

<sup>b</sup>British Water (2013)

<sup>c</sup>Comber *et al.* (2013)

<sup>d</sup>0.17lb/person/day converted to g. (Minnesota (n.d.))

<sup>e</sup>US. EPA (2002)

<sup>f</sup>Tolnai (2023)

As shown in **Table 10**, the PE values for OC, N, and P vary slightly across countries but remain within a similar range. These differences arise from national variations in domestic wastewater composition, driven primarily by factors such as the use of phosphate-based detergents, dietary patterns, and the prevalence of in-sink food waste macerators. Norway’s lower phosphorus PE value is of particular note, as it is lower than that of other nations due to its compliance with EU Regulation 648/2004 (European Union, 2004), which restricts the phosphorus content in laundry and dishwasher detergents, thereby reducing phosphorus loads in domestic sewage. As this study focuses on nutrient pollution in Norwegian coastal waters, Norwegian per-capita reference values were applied to ensure consistency with the pollutant composition expected in domestic wastewater entering

these systems.

All reference values are reported in grams per person per day, whereas the pollution data is recorded in tonnes per year. To derive annual population equivalence values, per-capita daily conversion factors were multiplied by 365 to obtain yearly values, which were then divided by 1,000 to convert from grams to kilograms. The conversion process is broken down in **Table 11**.

**Table 11.** Nutrient discharge factors and annual outputs.

Nutrient	PE Factor (g)	Per Year (g)	Per Year (kg)
Nitrogen	12	4380	4.38
Phosphorus	1.8	657	0.657
Organic Carbon	60	21900	21.9

Population equivalence (PE) for organic carbon (OC) was calculated using biochemical oxygen demand over five days (BOD<sub>5</sub>), in accordance with the definition applied in PE methodologies. BOD<sub>5</sub> represents the amount of oxygen required for the biological decomposition of biodegradable organic matter in water. In contrast, organic carbon in Norwegian monitoring data (TEOTIL3) is recorded as total organic carbon (TOC), which includes both biodegradable and non-biodegradable fractions (Boyles, 1997). As a result, TOC values are not directly compatible with BOD<sub>5</sub>-based PE calculations. To correct the difference, TOC values were converted to BOD<sub>5</sub> using a fixed conversion factor prior to PE calculation.

In this report, the conversion rate applied is BOD<sub>5</sub> = TOC × 1.8 (Siwiec *et al.*, 2018). The population equivalence for organic carbon was therefore calculated as:

$$PE(OC) = \frac{TOC \times 1.8}{21.9}$$

where TOC is expressed in kilograms per year, and 21.9 kg represents the annual per-capita BOD<sub>5</sub> load.

Population equivalents for nitrogen and phosphorus were calculated from total nitrogen (TN) and total phosphorus (TP), consistent with the units used in Norwegian pollution monitoring data (TEOTIL3). PE values for nitrogen and phosphorus were therefore calculated by using the formulae:

$$PE(TN) = \frac{TN}{4.38}$$

$$PE(TP) = \frac{TP}{0.657}$$

where TN and TP are expressed in kilograms per year, and 4.38 kg and 0.657 kg represent the annual per-capita TN and TP load, respectively.

This methodology applies nationally reported per-capita wastewater emission factors, assumed to

be temporally stable and representative of Norwegian domestic wastewater inputs. Population equivalence is used as a normalisation and reporting metric to express observed aquaculture-derived nutrient loads in comparable terms, without implying equivalence in source characteristics or environmental behaviour. Within this framework, PE provides a consistent and transparent basis for comparison of pollution metrics.

## 4.9. Results Quality Review

Multiple quality assurance measures were implemented throughout the analysis to ensure accuracy and reproducibility. All datasets were verified against source files from Fiskeridirektoratet and Veterinærinstituttet, with download dates recorded for traceability. Data processing scripts include automated checks for missing values, outliers, and inconsistencies that trigger warnings during execution. Unit tests were run on all core calculation functions to verify mathematical accuracy, including known input-output pairs, and edge cases such as zero mortality. Results were compared against TEOTIL3 reference values for all available years, with discrepancies exceeding 3% triggering manual review. Complete code documentation was maintained in the project repository via function-level docstrings, inline comments, and a comprehensive methodology document that linked equations to their implementations. All analysis code, data processing scripts, and intermediate outputs are publicly available on Sunstone Institute's GitHub, allowing any researcher with access to the same input datasets to reproduce all results by executing the documented analysis pipeline. This validation approach provides high confidence that the reported nutrient waste values accurately represent the environmental loading from Norwegian aquaculture for the 2020–2025 period.

Additionally, an independent expert review was conducted throughout the project by external experts with specialised domain knowledge in marine biology and ecology, as shown in **Table 12**. These experts provided technical guidance throughout the project, contributing to methodology development, data interpretation, and validation of results. Beyond the expert panel, the analytical team included data scientists and data analysts, with additional contributions from journalists and underwater photographers to support contextual understanding and effective communication of findings (**Table 13**).

**Table 12.** External experts panel for the nutrient analysis project.

Name	Company	Role	Field of expertise
Hartvig C Christie	NIVA	Senior Researcher	Marine Biology
Tom N. Pedersen	Statsforvalteren	Senior advisor	Ecology, Aquaculture

**Table 13.** Nutrient Analysis team (excluding experts).

Name	Company	Role	Field of expertise
Aleksander Nordahl	Sunstone Institute	Journalist	Investigative Journalism, Underwater Documentation
Alexandra Pires Duro	Sunstone Institute	Data Scientist	Data Science
Carter Brown	Sunstone Institute	Data Analyst	Data Analysis
Ingerid Salvesen	Sunstone Institute	Editor	Investigative journalism
Lou Luddington	Freelancer	Journalist	Marine Biology Journalism

## 5. Results and Findings

All results presented in this section represent national-level aggregates across Norwegian coastal aquaculture operations. The report quantifies total nutrient discharge for the aquaculture industry and does not provide regional or site-specific breakdowns.

### 5.1. Annual Nutrient Discharge

**Table 14** presents the mass balance results for Norwegian aquaculture over the six-year analysis period. Annual nutrient waste discharge is proportional to feed consumption, reflecting the relationship between feed inputs and environmental outputs within the mass balance framework.

**Table 14.** Annual nutrient discharge.

Year	Feed (tonnes)	N Waste (tonnes)	P waste (tonnes)	OC Waste (tonnes)
2020	1 996 297	66 781	11 593	313 998
2021	2 046 506	68 236	11 850	321 895
2022	2 000 682	65 985	11 475	314 687
2023	2 060 552	68 181	11 852	324 104
2024	2 129 036	70 386	12 237	334 876
2025	2 288 296	75 382	13 111	359 926

## 5.2. Temporal Trends (2020-2025)

Feed consumption increased by 14.63% from 2020 to 2025, rising from 1,996,297 tonnes to 2,288,296 tonnes. Nitrogen waste increased by 12.88% over the same period (66,781 to 75,382 tonnes), while phosphorus waste increased by 13.09% (11,593 to 13,111 tonnes). Organic carbon waste followed a similar trajectory, increasing 14.63% from 313,998 to 359,926 tonnes. Notable year-to-year variation is observed, particularly between 2021 and 2022, when both feed consumption and waste discharge decreased despite the overall upward trend.

Annual rates of change remained consistent across all three waste parameters between 2020 and 2024, with year-to-year variation not exceeding  $\pm 3.4\%$ .

## 5.3. Feed Efficiency and Retention

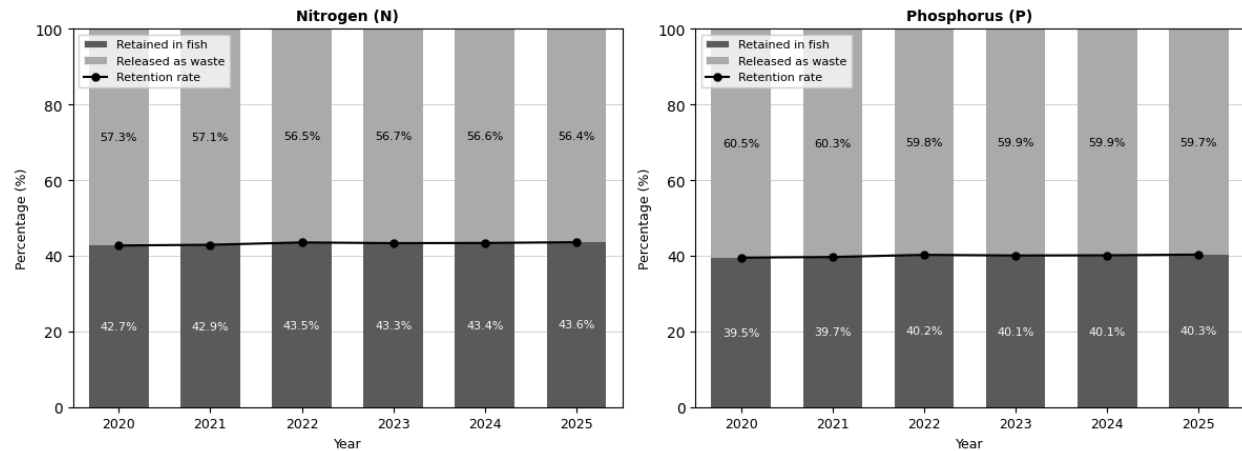
Feed efficiency metrics quantify the proportion of nutrients supplied through feed that are retained in fish biomass (slaughter, biomass change, and mortality) relative to those released to the environment as waste. These metrics provide insight into the environmental performance of aquaculture operations and indicate inefficiencies in nutrient transfer in biological production systems.

### 5.3.1. Nutrient Retention Patterns

Nitrogen retention averaged 43.25% over the six years, with approximately 57% of the nitrogen supplied through feed being released to the environment as waste. Phosphorus retention was consistently lower, averaging 39.99%, with approximately 60% of the phosphorus released as waste. Annual retention rates showed minimal variation across the analysis period, ranging from 42.72% to 43.59% for nitrogen and 39.51% to 40.31% for phosphorus. **Table 15** and **Figure 2** illustrate the annual distribution of the retained and wasted fractions of nitrogen and phosphorus across the analysis period.

**Table 15.** Feed efficiency metrics.

Year	N Retention (%)	P Retention (%)	N Waste Rate (%)	P Waste Rate (%)
2020	42.72	39.51	57.28	60.49
2021	42.91	39.68	57.09	60.32
2022	43.53	40.25	56.47	59.75
2023	43.34	40.08	56.66	59.92
2024	43.39	40.13	56.61	59.87
2025	43.59	40.31	56.41	59.69

**Figure 2.** Annual distribution of the retained and wasted fractions of N and P (2020–2025).

Organic carbon waste was calculated using a fixed empirical waste factor (32.1%), following the approach detailed in the Methodology section. Retention and waste rates were therefore not independently calculated from feed inputs and outputs, so direct comparison with the mass balance results for nitrogen and phosphorus is not possible.

### 5.3.2. Temporal Improvements

Both nitrogen and phosphorus retention show modest improvements over the analysis period. Nitrogen retention increased from 42.72% in 2020 to 43.59% in 2025, representing a 0.87 percentage point increase. Phosphorus retention increased from 39.51% to 40.31%, a 0.80 percentage point improvement. A 1-point increase in nitrogen retention would reduce annual nitrogen waste by approximately 1,300 tonnes.

Retention rates reached a local maximum in 2022 (43.53% for nitrogen, 40.25% for phosphorus), followed by slight declines in 2023 and partial recovery in 2024, before reaching their highest values of the analysis period in 2025 (43.59% and 40.31%, respectively).

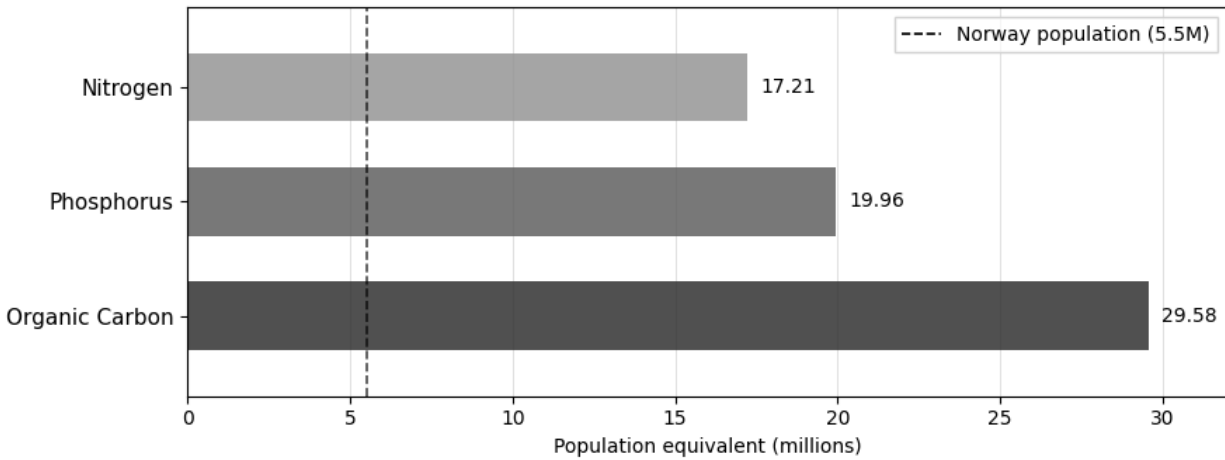
## 5.4. Population Equivalence

In 2025, Norwegian aquaculture released 75,382 tonnes of nitrogen, 13,111 tonnes of phosphorus, and 359,926 tonnes of organic carbon into coastal waters. For scale reference, the nitrogen, phosphorus, and organic carbon discharges correspond to 3.13, 3.63, and 5.38 times, respectively, the untreated domestic sewage load of approximately 5.5 million people (Norway's population). **Table 16** and **Figure 3** present aquaculture nutrient waste, expressed as population equivalents (millions of people), for the aforementioned nutrients across the analysis period, illustrating the scale of nutrient discharge relative to untreated human sewage.

**Table 16.** Aquaculture waste in Population Equivalents per year, in millions of people.

Year	Nitrogen Equivalent	Phosphorus Equivalent	Organic Carbon Equivalent
2020	15.25	17.65	25.81
2021	15.58	18.04	26.46
2022	15.07	17.47	25.86
2023	15.57	18.04	26.64
2024	16.07	18.63	27.52
2025	17.21	19.96	29.58

These discharge levels reflect only the nutrients released into the environment and do not account for the significant nutrient amounts retained in harvested fish (slaughter) or standing biomass. Additionally, they represent untreated sewage equivalents.

**Figure 3.** Nutrient discharge expressed as PE (2025).

## 6. Validation

### 6.1. Validation Methodology

Model validation employed two metrics to assess agreement between calculated values and TEOTIL3 reference data across validation years (2020–2023, n=4):

#### Mean Absolute Percentage Error (MAPE)

$$MAPE = \frac{1}{n} \times \sum \left| \frac{y_i - \hat{y}_i}{y_i} \right| \times 100$$

Where  $y_i$  represents the TEOTIL3 reference value, and  $\hat{y}_i$  represents the calculated value for year  $i$ . MAPE quantifies the mean absolute percentage difference between predicted and observed values.

#### Root Mean Squared Error (RMSE)

$$RMSE = \sqrt{\frac{1}{n} \times \sum_{i=1}^n (y_i - \hat{y}_i)^2}$$

RMSE quantifies the magnitude of prediction error in the original units (tonnes). RMSE was converted to a percentage of the mean reference value for direct comparison with the tolerance threshold:

$$RMSE\% = \frac{RMSE}{\bar{y}} \times 100$$

Where  $\bar{y}$  represents the mean TEOTIL3 reference value across all validation years.

A tolerance threshold of  $\pm 3\%$  was established a priori based on the study's objective to reproduce TEOTIL3 calculations within acceptable margins for environmental modelling applications.

### 6.2. TEOTIL3 Model Comparison

Validation was conducted against the TEOTIL3 model developed by NIVA (Sample, 2025). Both models calculate national totals for OC, N, and P waste across all Norwegian coastal waters. TEOTIL3 reference values were obtained for the years 2020–2023. Values for 2024–2025 were not available at the time of analysis.

### 6.3. Validation Results

**Table 17.** Model validation against TEOTIL3 (2020–2023).

Nutrient	MAPE (%)	RMSE (%)
Organic Carbon	0.00	0.01
Nitrogen	1.70	1.80
Phosphorus	1.49	1.57

Note: All metrics within 3% tolerance threshold. n = 4 years (2020–2023).

As shown in **Table 17**, Nitrogen waste calculations showed a MAPE of 1.70% and an RMSE of 1.80% relative to the TEOTIL3 reference values. Phosphorus calculations showed MAPE of 1.49% and RMSE of 1.57%. Organic carbon calculations showed MAPE of 0.00% and RMSE of 0.01%.

All validation metrics fall within the a priori established 3% tolerance threshold. The systematic positive bias observed for nitrogen and phosphorus (calculated values consistently higher than TEOTIL3) likely reflects minor differences in rounding procedures or data handling.

The mass balance approach employed in this study reproduces TEOTIL3 outcomes within established tolerance limits. Calculations for 2024 and 2025 apply the same validated methodology using actual data inputs from those years.

## 7. Discussion

### 7.1. *Environmental Implications*

The scale of nutrient discharge documented in this study, 75,382 tonnes of nitrogen and 13,111 tonnes of phosphorus, 359,926 tonnes of organic carbon, in 2025, places Norwegian aquaculture among the most significant anthropogenic nutrient sources to Norway's coastal waters. As demonstrated in the population equivalence calculation results (**Table 16**), these inputs exceed the untreated sewage equivalent of Norway's entire population by a factor of 3.13, 3.63, and 5.38 for nitrogen, phosphorus, and organic carbon, respectively, documenting the industry's environmental footprint alongside its economic contribution.

Moreover, this scale of discharge reflects sustained production growth over the six-year analysis period. Feed consumption increased by 14.63% from 2020 to 2025, reflecting the continued expansion of Norwegian aquaculture production capacity and increased stocking density at existing facilities. Nitrogen and phosphorus waste increased at lower rates, indicating marginal improvements in nutrient retention efficiency. This pattern suggests improvements in feed conversion ratios or changes in production practices that reduce waste. Shifts in harvest and stocking timing affecting annual biomass change calculations may also contribute. The decline observed between 2021 and 2022 likely reflects market conditions and disease events, possibly compounded by regulatory constraints, that temporarily reduced production volumes.

Notably, the lower phosphorus retention compared to nitrogen (40.31% vs. 43.59%) reflects fundamental disparities in how these nutrients are metabolised and excreted by fish. Phosphorus is primarily excreted through urine as soluble inorganic phosphate, with faecal phosphorus being mostly insoluble and of lower environmental concern. At the same time, nitrogen is lost mainly as ammonia via the gills, with additional losses through faeces and uneaten feed (Sugiura, 2025). The differential retention rates demonstrate that feed formulations contain phosphorus in slight excess of fish physiological requirements, resulting in higher proportional waste discharge relative to nitrogen.

Wang *et al.* (2012) reported 38% nitrogen and 30% phosphorus retention (equivalent to 62% and 70% waste rates, respectively) for Norwegian salmon farms in 2009. Our findings show higher retention efficiency, suggesting either methodological differences or improvements in feed efficiency over the past decade. However, the nutrient retention challenge persists: current open-net cage systems inherently release more than half of the input nutrients to the environment.

Despite modest improvements in retention rates (0.87 percentage point gain for nitrogen, 0.80 for phosphorus from 2020–2025), waste discharge increased by 12.88% (nitrogen) and 13.09% (phosphorus) from 2020–2025, driven by 14.63% growth in feed consumption, indicating that increased production volumes offset efficiency gains.

Staalstrøm *et al.* (2025) established that aquaculture nutrients account for two-thirds of observed oxygen depletion in Norwegian fjords, providing direct mechanistic evidence linking the waste quantities documented here to measurable ecosystem degradation. Our results quantify the nutrient driver underlying this hypoxia, offering a foundation for evidence-based regulation and mitigation

strategies.

The aggregate national estimates presented do not capture spatial variation in discharge patterns and local environmental conditions. Norwegian aquaculture is geographically concentrated in coastal and fjord regions with lower population densities than urban centres (Fiskeridirektoratet, n.d.), resulting in nutrient discharges into environments with different baseline anthropogenic conditions than those receiving most municipal wastewater. Regional-scale analysis of spatial impacts, site-specific assimilative capacity, and cumulative effects on individual fjord systems will be addressed in subsequent publications.

## 7.2. Comparison with Reference Models

Our model's implementation of the aggregate mass balance approach (validated against TEOTIL3 with all metrics  $\leq 1.80\%$ ) demonstrates that this simplified framework achieves comparable accuracy without requiring detailed waste component partitioning. Compared to partitioned approaches such as those of Wang *et al.* (2012), our methodology requires fewer assumptions about assimilation efficiencies and particle dissolution rates, making it well-suited for ongoing monitoring and rapid scenario analysis while producing results consistent with the established TEOTIL3 reference model.

Our retention rates differ from those reported by Wang *et al.* (2012) for Norwegian salmon farms in 2009 (38% nitrogen, 30% phosphorus retention). Retention rates in our dataset remained consistent across the six years (nitrogen: 42.72–43.59%; phosphorus: 39.51–40.31%). The sources of these differences are unclear and may stem from variations in feed composition, regional production practices, fish populations, measurement methods, or time periods.

Wang *et al.* (2012) found that nitrogen waste is predominantly released as dissolved inorganic nitrogen (DIN) through excretion (approximately 45% of feed N), while phosphorus waste is predominantly particulate (approximately 44% of feed P). These findings describe the distribution of nutrient waste components that comprise the total waste values calculated in this study.

Notably, our model does not partition waste into dissolved and particulate fractions as Wang *et al.* (2012) did. While their detailed partitioning (45% DIN, 15% PON for nitrogen; 18% DIP, 44% POP for phosphorus) provides insights into bioavailability and environmental fate, total waste quantification is sufficient for regulatory compliance assessment and population equivalence. Future work could incorporate speciation modelling if site-specific biogeochemical assessment is required.

## 7.3. Uncertainties and Limitations

Three primary sources of uncertainty affect these calculations, as detailed previously:

1. Feed consumption data are reported without explicit phase-level stratification, while biomass measurements are restricted to sea-phase stocks. This asymmetry in reporting resolution introduces potential for phase-allocation bias. Specifically, if hatchery-phase feed consumption is aggregated with sea-phase totals in the reported dataset but excluded from

biomass change calculations (which measure only sea-phase standing stock), the resulting mass balance would overestimate nutrient waste discharge.

2. The magnitude of this potential bias cannot be directly quantified without phase-stratified reporting from Fiskeridirektoratet. While model validation against TEOTIL3 reference values fell within a  $\pm 3\%$  tolerance (see the Validation section), this validation does not directly address the phase-allocation issue, as both the Sunstone model and TEOTIL3 operate under the same reporting constraints. Consequently, this limitation constitutes a structural source of uncertainty that persists regardless of model agreement. Resolution would require the data provider to provide explicit documentation of feed allocation by production phase.
3. Mortality weight estimates are derived from multi-year datasets and may not fully capture interannual variation in mortality timing or growth performance. Regional differences in temperature regimes, husbandry practices, and disease pressure can influence both mortality rates and average weight at death. The use of unweighted bin-midpoint averages from binned mortality data inherently introduces estimation error relative to individual fish-based measurements. However, sensitivity analysis indicates that alternative mortality weight scenarios across adjacent weight bins yield variations in waste ranging from +2.80% to -2.11% for nitrogen and +2.45% to -1.85% for phosphorus, confirming that mortality parameters do not represent a significant source of uncertainty in the mass balance calculations.
4. Applying unified coefficients to both salmon and trout is justified by salmon's dominance, but it introduces minor uncertainty in trout-specific estimates. Species-differentiated modelling would require separate mortality-weight distributions, which are not currently available in published surveillance data.

Despite these limitations, the successful TEOTIL3 validation demonstrates that aggregate uncertainties remain within acceptable bounds for national-scale environmental assessment.

## *7.4. Implications for Aquaculture Management*

The documented nutrient loads and 57–60% waste rates highlight the environmental implications of current production intensities. Improvements in feed conversion efficiency (achieved through optimised feeding regimes, selective breeding for nutrient retention, or the adoption of lower-phosphorus feed formulations) would result in measurable absolute reductions in nutrient discharge.

Current regulatory frameworks primarily focus on benthic impacts, which capture the particulate fraction. The dissolved nutrient fraction contributes to water column eutrophication and is not currently subject to direct discharge limits.

## 8. Conclusions

This study quantified nutrient waste discharge from Norwegian aquaculture for 2020–2025 using a validated mass balance approach. In 2025, the industry released 75,382 tonnes of nitrogen, 13,111 tonnes of phosphorus, and 359,926 tonnes of organic carbon to coastal waters, equivalent to sewage from 17.21 million, 19.96 million, and 29.58 million people, respectively.

All calculations met the  $\pm 3\%$  validation criterion relative to the TEOTIL3 reference model, confirming methodological consistency. The approach developed provides a reproducible framework for ongoing environmental monitoring and regulatory assessment, without the computational complexity of detailed nutrient partitioning models.

Feed efficiency analysis revealed that current production systems retain 43% of nitrogen and 40% of phosphorus in fish biomass, with the remaining 57–60% released into the environment. While modest improvements were observed during the analysis period, the inherent nutrient retention characteristics of open-net cage systems remain the primary factor driving coastal nutrient loading. This pattern additionally indicates that technological advancements alone cannot offset the environmental impact of production expansion under current open-net cage systems.

## Acknowledgments

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