

Harmonized Life Cycle Assessment Guideline for Omega-3 Supply Chains

The Global Organization for EPA
and DHA Omega-3s (GOED)

Prepared by
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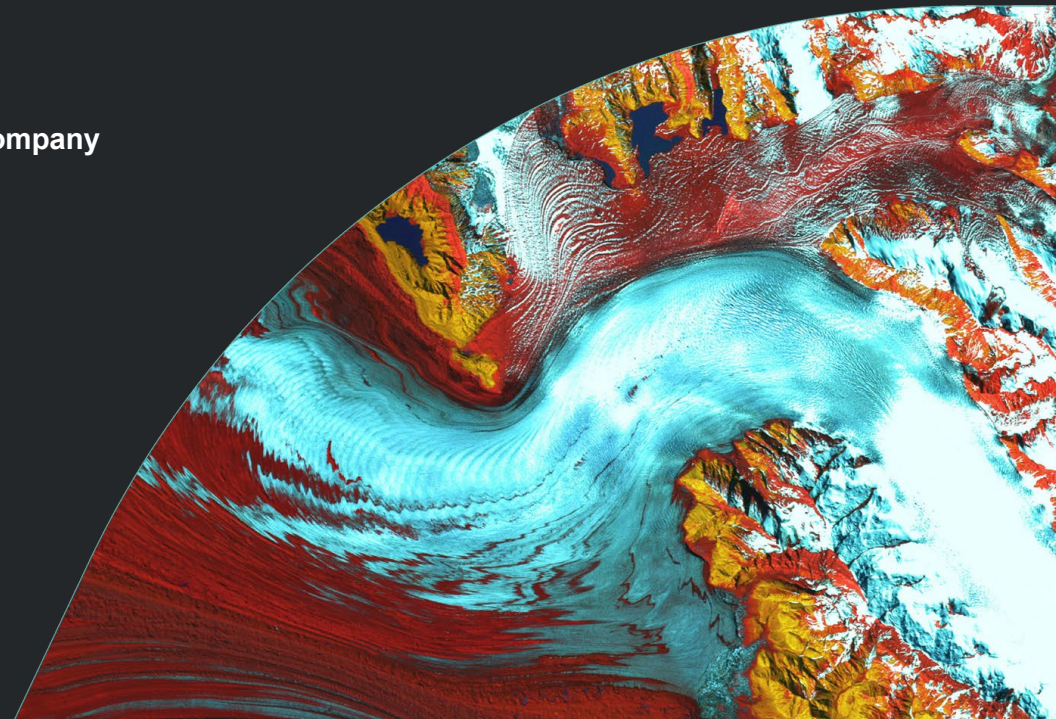


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Acronyms and Definitions

CH₄	Methane
CO₂	Carbon dioxide
CO₂e	Carbon dioxide equivalent
DHA	Docosahexaenoic acid
DQI	Data quality indicator
DtT	Distance to target
EF	Environmental footprint
EN	European normalization
EPA	Eicosapentaenoic acid
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
FEDIAF	European Pet Food Industry Federation
FU	Functional unit
GHG	Greenhouse gas
GOED	The Global Organization for EPA and DHA Omega-3s
GWP	Global warming potential
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

LC-PUFAs	Long-chain polyunsaturated fatty acids
N₂O	Nitrous oxide
NO_x	Nitrogen Oxides
NH₃	Ammonia
PBR	Photobioreactor
PCR	Product Category Rule
PEFCR	Product Environmental Footprint Category Rules
ReCiPe	A LCIA method that was initially developed in 2008 through a collaboration between several Dutch and international organizations including National Institute for Public Health and the Environment, Netherlands and Radboud University, Nijmegen, University of Leiden, and PRé Sustainability
SO₂	Sulfur Dioxide
SOC	Soil Organic Carbon
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRL	Technology Readiness Level
USDA	U.S. Department of Agriculture
USEtox	A consensus model for human toxicity and ecotoxicity characterization in LCA, developed by UNEP-SETAC
USLCI	U.S. Life Cycle Inventory Database
VOC	Volatile Organic Compound

Glossary: International Organization for Standardization (ISO) 14040/44:2006

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

Life cycle: “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1).

Life Cycle Assessment (LCA): “Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2).

Life Cycle Inventory (LCI): “Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3).

Life Cycle Impact Assessment (LCIA): “Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4).

Life Cycle Interpretation: “Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5).

Functional Unit (FU): “Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20).

Allocation: “Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17).

System Boundary: “Set of criteria specifying which unit processes are part of a product system” (ISO 14040:2006, section 3.32). “Examples are cradle-to-gate studies, gate-to-gate studies, and specific parts of the life cycle...” (ISO 14040:2006, section A.1.2).

Reference Flow: “Measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit” (ISO 14044:2006, section 3.29).

Release: “Emissions to air and discharges to water and soil” (ISO 14044:2006, section 3.30).

Impact Categories: “Class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” (ISO 14044:2006, section 3.39).

Executive Summary

The global omega-3 industry includes a variety of sources of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are currently produced from a wide range of marine, microbial, and agricultural sources. While this innovation strengthens supply resilience and sustainability goals, it has also led to a fragmented landscape on life cycle assessment (LCA) approaches, assumptions, and system boundaries. These inconsistencies can limit the comparability, transparency, and credibility of environmental claims across the sector.

To address this challenge, the Global Organization for EPA and DHA Omega-3s (GOED), in collaboration with LRQA and EcoEngineers, has developed a harmonized, ISO-aligned LCA methodological guideline for omega-3 supply chains. This guideline provides a common technical framework to ensure that product carbon footprints and broader environmental impact assessments are consistent, robust, and useful in decision-making, regardless of production pathways.

This guideline establishes a standardized approach for conducting cradle-to-gate LCAs of omega-3 products, from raw material extraction through refined oil or ingredient output. It is designed to support:

- Fair and transparent comparison of environmental performance of omega-3 sources
- Identification of environmental hotspots and improvement opportunities
- Credible sustainability communication and reporting
- Alignment with ISO 14040/44 principles and requirements for conducting life cycle impact assessments

The guidance applies across the full diversity of omega-3 production systems, including marine animal, algal, and oilseed-based pathways, and it is intended for use by industry practitioners, consultants, and third-party reviewers. To ensure consistency across diverse technologies, the framework provides pathway-specific guidance for marine animal-based, algae-based, and oilseed-based (e.g., canola) omega-3 production systems, capturing their distinct inputs, processing steps, and environmental drivers.

All studies conducted under this framework must transparently document assumptions, data sources, study period, description of the production process and its system boundaries, location, modeling choices, and key limitations. The guideline is intended to evolve alongside scientific advances, regulatory changes, and industry best practices, serving as a living reference for credible environmental performance evaluation.

Section 1: Introduction and Overview

This guideline is prepared by LRQA and EcoEngineers at the request of the Global Organization for EPA and DHA Omega-3s (GOED), primarily aiming to develop a life cycle assessment (LCA) methodological guide for omega-3 member industries. This guideline offers overarching technical guidance consistent with the ISO 14040/14044 (2006) standards for conducting LCA of the Omega-3 supply chain. Its primary objective is to establish a common foundation for generating harmonized life cycle inventory (LCI) data and conducting robust LCA studies. It is expected to support coherent and reliable sustainable production and consumption policies, as well as informed decision-making in both public and private sectors concerning products, resources, and waste management.

1.1: Scope of the Guideline

This general guideline provides methodological provisions for formulating LCI and conducting LCA studies, as defined by ISO 14040 and ISO 14044:2006. It is intended to support GOED and its member companies in conducting consistent and comparable LCAs of targeted omega-3 products. The guideline establishes an overarching LCA framework and outlines key methodological considerations specific to omega-3 supply chains from select sources.

1.2: Omega-3 Importance and Feedstock Considerations

Omega-3 long-chain polyunsaturated fatty acids (LC-PUFAs), specifically eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), are widely recognized for their essential role in both human and animal health (Swanson et al., 2012). These fatty acids support a range of critical physiological functions: DHA is vital for brain and eye development, cognitive performance, and neural function, while EPA is valued for its anti-inflammatory properties and cardiovascular benefits. Together, EPA and DHA contribute to cellular membrane integrity, immune system modulation, blood pressure regulation, and overall metabolic health (Swanson et al., 2012; Calder, 2015).

Traditionally, marine sources such as fish oil (e.g., anchovies, sardines, tuna), and krill have been the primary supply of EPA and DHA. However, to meet growing global demand across the pharmaceutical, nutraceutical, functional food, and animal nutrition sectors, the industry has increasingly turned to alternative production pathways, including microalgae cultivated under controlled-conditions and genetically optimized plant seed oils that can produce EPA and/or DHA directly (Davis et al., 2021; Togarcheti & Padamati, 2021).

This guideline mainly focuses on three types of feedstock sources to produce omega-3: marine animal sources (fish and krill), algae, and oilseeds. For each type of feedstock source, this guideline illustrates the diversifications in feedstock sourcing and production technologies inherent with the selected supply chain.

1.3: Rationale for Applying LCA to Omega-3 Supply Chains

The omega-3 sector is characterized by a diverse array of supply chains, encompassing various sources such as marine, algae, and genetically modified oilseed crops. This diversification introduces substantial variability in energy and resource consumption, raw material inputs, such

as land and water use, co-product generation, technological maturity, and geographic context. These factors significantly influence the overall environmental footprints of omega-3 production, necessitating a robust and consistent methodological guideline to assess and compare the environmental performance of different sources.

LCA offers a scientifically rigorous and internationally recognized framework for evaluating the environmental impacts of products throughout their life cycle, starting from raw material extraction and cultivation to processing, distribution, and, where applicable, end-of-life. In the context of omega-3 production and similar production systems, LCA enables the identification of environmental hotspots, supports adoption of more sustainable production practices, and provides credible data for regulatory compliance, corporate sustainability initiatives, and product environmental claims, as necessary.

Although the application of LCA to EPA and DHA production has expanded in recent years, the sector's complexity has led to inconsistencies in study design (Togarcheti & Padamati, 2021). Variations in system boundaries, allocation methods, functional units, and data sources reflect the innovative and evolving nature of the industry but also pose challenges for cross-study comparisons. Establishing a harmonized methodological guideline presents a valuable opportunity to align best practices, improve data consistency, and facilitate meaningful benchmarking across the sector. Moreover, a standardized approach enhances the transparency and credibility of environmental communications to external stakeholders, including regulators, customers, investors, and sustainability standards organizations, by ensuring that environmental claims are based on consistent, high-quality, and comparable data.

GOED recognized the need for standardized framework to pursue LCA and initiated the development of a guideline for consistent methodology to support a standardized, replicable, transparent, and comprehensive approach to conducting LCAs of omega-3 production systems focusing exclusively on EPA and DHA. The primary objective of such framework is to inform industry stakeholders, regulators, and sustainability auditors on best practices for sustainable sourcing, processing, and distribution of omega-3 products.

1.3.1: Intended Use Cases

This guideline is prepared to serve EPA and DHA omega-3 production stakeholders globally regardless of the production technology used. It aims to support industry stakeholders in generating reliable and comparable environmental data, facilitate sector-wide alignment on sustainability metrics, and strengthen the industry's collective commitment to environmental responsibility and continuous improvement. During the LCA modeling phase, stakeholders are expected to apply the guideline, while appropriately customizing relevant components of the omega-3 supply chain reflecting their specific organizational and operational system boundaries.

The following sections provide detailed illustrations of key LCA features and explain the application of LCA framework and principles to specific feedstock-based omega-3 supply chains.

In this guideline, provisions are categorized according to their level of requirement, following the guidance of the International Reference Life Cycle Data System (ILCD) Handbook (EC, 2010): "Shall" refers to mandatory requirement, unless explicitly stated otherwise. "Should" refers to

expected requirement; deviations are permitted only with written justification and proper documentation. “May” refers to optional recommendation; no justification required. “Recommended” is used with the same meaning.

Section 2: Fundamentals of Life Cycle Assessment

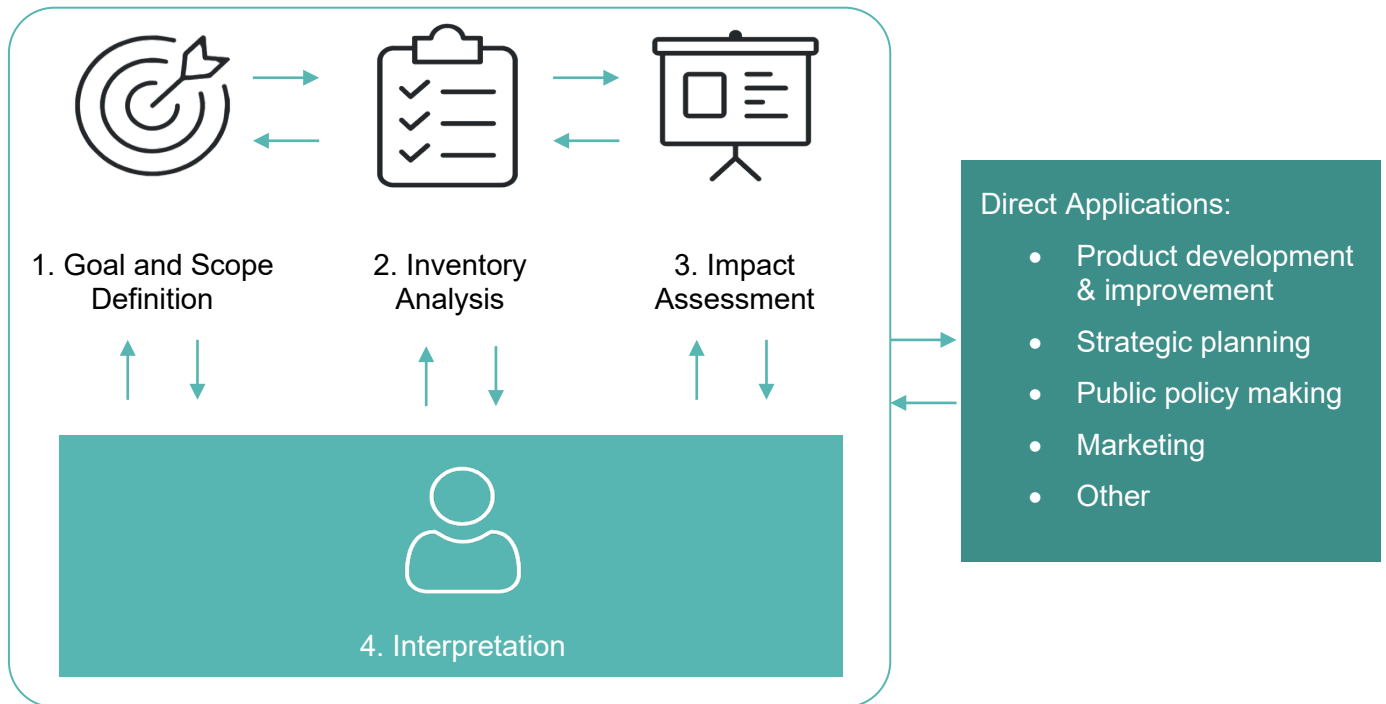
LCA is a systematic methodology used for the compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system (ISO 14040/44:2006). The evaluation is focused throughout a product life cycle constituting raw material extraction, production, and use, to end-of-life disposal or recycling, as relevant. It provides a comprehensive view of the environmental aspects and potential impacts, enabling informed decision-making for sustainable development.

An LCA study consists of four phases:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation

Each phase is discussed in detail in the following sections (Figure 1).

Figure 1: Framework for LCA and Application Areas



- ISO 14040:2006

This chapter defines methodological principles that apply across all omega-3 supply chains (marine animal-based, algae-based, and oilseed-based). These rules are intended to ensure

consistency, transparency, and comparability across studies and shall be applied unless explicitly justified otherwise in the supply chain-specific sections (Section 3: Supply-Chain Specific Guideline).

2.1: Goal and Scope Definition

2.1.1: Goal of Study

The goal of an LCA shall be clearly defined and consistent with its intended application, in accordance with ISO 14040 and ISO 14044. Given the iterative nature of an LCA, elements of the goal and scope may be refined as the study progresses, provided that any changes are documented and adjusted.

The goal definition shall specify:

- The intended application of the study (e.g., environmental footprinting, benchmarking, environmental reporting, product development, labeling, policy support)
- The rationale for conducting the study
- The target audience and stakeholders to whom the results will be communicated
- Whether the results are intended to be used for comparative assertions disclosed to the public, and therefore the need for a critical review

The intended application forms the foundation for establishing the study's goal and directly influences key methodological choices. A clearly defined goal ensures that the LCA is focused, transparent, relevant, and capable of delivering meaningful insights for decision-making processes.

For omega-3 products, the goal of an LCA study shall explicitly state the product type and supply chain under assessment (e.g., fish and krill-, algae-, or oilseed-based omega-3), as well as the specific objectives of the study for each pathway.

Where results are intended to support comparative assertions and to be disclosed publicly, a critical review shall be conducted in accordance with ISO 14044 and ISO/TS 14071:2014, where additional critical review requirements and guidelines are provided in detail. The type and scope of review should be determined based on the intended application of the study.

2.1.2: Scope of Study

The scope of an LCA study shall define the key assumptions, methodological choices, and level of detail necessary to achieve the stated goal, in accordance with ISO 14040/14044 (2006). The scope establishes the context within which the assessment is conducted and ensures transparency and consistency across studies.

The scope shall include a clear description of the product system under the study, its function, the functional unit used for analysis, and the system boundaries defining the life-cycle stages and processes included in the assessment. For omega-3 products, the scope shall also identify the relevant feedstock-based supply chain(s) under evaluation (e.g., fish and krill-, algae-, or oilseed-based) and the production processes covered. Supply chain-specific requirements and

necessary elements are further detailed in the corresponding pathway descriptions (see Section 3: Supply-Chain Specific Guideline).

In addition, the scope shall highlight the overarching methodological approaches applied in the study, including allocation procedures for multi-output or shared processes, the selected LCIA method, and interpretation approach. The scope shall also outline the data requirements, assumptions, value choices, limitations, and data quality expectations. Where a critical review is planned, the scope shall indicate its type and extent as well as the intended format of the final report. Given the iterative nature of LCA, revisions to the scope may be necessary as new information or constraints arise; any such changes must be documented and justified. Key elements of the scope are discussed in the following sections.

2.1.3: System Boundary, Functional Unit, and Reference Flow in LCA

The system boundary, functional unit, and reference flow are fundamental elements of an LCA study and shall be defined in a manner consistent with the stated goal, in accordance with ISO 14040 and ISO 14044. Together, they establish the basis for quantifying inputs, outputs, and environmental impacts and ensure consistency and comparability across studies.

2.1.3.1: Product System Description

The product system should illustrate how it represents the production of omega-3 fatty acid ingredients (EPA and DHA), and if they are intended for use in dietary supplements and food applications. It should also provide a description of that system that begins with the sourcing of biological feedstocks (e.g., marine organisms, oilseed crops, or carbon sources for algae) and includes all upstream and on-site processes required to produce the final omega-3 product in its different forms (e.g., concentrate, powder, liquid suspension) as well as any co-product, by-product or waste generated as a result of those processes.

Omega-3 processing and enrichment involves the concentration of EPA and DHA through chemical, physical, or enzymatic methods, followed by formulation of DHA, EPA, or combined EPA+DHA products, and packaging and storage of the finished ingredients. Depending on the final product specification, formulation may require supplemental carrier oils and additional inputs such as chemicals, water, energy, fuels, and refrigeration. Depending on the boundary of the supply chain, necessary LCI data should be collected and considered for LCIA.

The primary outputs are focused on omega-3 products. Co-products may include other fatty acid fractions, protein meals, animal feed ingredients, or residual biomass. Supporting processes such as energy generation, chemical production, packaging material manufacturing, cold storage, and transportation between life-cycle stages are included.

Downstream product use and end-of-life are excluded under the default cradle-to-gate boundary unless otherwise specified.

2.1.3.2: Functional Unit

The functional unit (FU) defines the quantified performance of the product system and serves as the reference to which all inputs and outputs are normalized (ISO 14040/44:2006). Once the FU is established, the corresponding reference flow (i.e., the amount of product required to fulfill the

FU) shall also be defined. Both the FU and reference flow shall be consistent with the selected system boundary (Figure 2).

For comparative studies, all scenarios and products shall be evaluated using the same FU. If certain functions are excluded from the comparison, this shall be clearly documented. Alternatively, the system boundary may be expanded to include additional processes that deliver equivalent functionality, with transparent justification.

This guideline recommends using a mass-based functional unit of “1 milligram, gram or kilogram of EPA or DHA or EPA+DHA omega-3 fatty acids expressed as free fatty acid equivalents delivered at the factory gate.” This functional unit reflects the primary function of the omega-3 product under assessment and is consistent with the selected cradle-to-gate system boundary. It also enables comparability across different production pathways (e.g., fish oil-, krill oil-, algal oil-, and oilseed-based systems) under a harmonized scope. If essential product properties such as EPA+DHA concentration differ across comparative scenarios, these differences shall be clearly identified and transparently reported.

For multi-output systems, the functions of all co-products shall be considered, and allocation of inputs and emissions may be required. The chosen method shall be justified, documented, and applied consistently. Detailed guidance on allocation is provided in Section 2.2.3.2: Allocation in Multi-Product Systems.

2.1.3.3: System Boundary

The system boundary defines which unit processes are included in the LCA. The criteria used to set these boundaries shall be clearly identified and justified.

This guideline adopts cradle-to-gate as the default system boundary to ensure consistency and comparability across omega-3 supply chains. This includes all processes from feedstock production or harvesting through final omega-3 ingredient manufacturing and packaging at the factory gate (Section 3: Supply-Chain Specific Guideline). However, in general, LCA studies cover varying and broader spectrum of supply chain and study scopes (e.g., gate-to-gate, cradle-to-grave or cradle-to-cradle), which may be used when aligned with the study goal and intended application, but deviations from the default boundary shall be transparently reported (Figure 2).

The system boundary comprises:

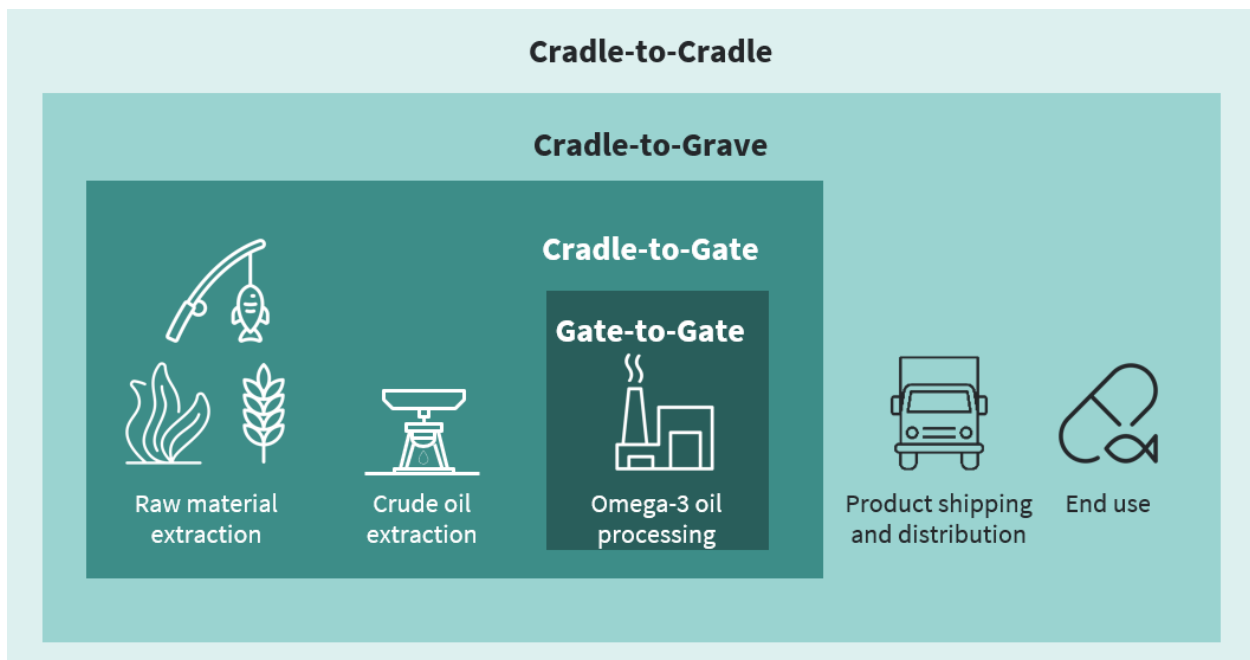
- **Foreground system:** Includes processes directly controlled or influenced by the subject of study, for which primary data are typically collected (e.g., algae cultivation, fishing operations, onsite energy consumption, oil extraction, formulation).
- **Background system:** Includes processes outside direct control, such as electricity generation, fertilizer production, fuel supply, and chemical manufacturing, generally modeled using secondary LCA databases. The background system provides a broader supply-chain context for the foreground processes.

Depending on the study goal, the system boundary may include the following with respect to omega-3 oil production:

- **Upstream processes:** fishing or cultivation (e.g., wild-caught fish and krill or algae farming, or oilseeds farming) and transportation of raw materials
- **Midstream processes:** extraction and purification of omega-3 oils, encapsulation, and packaging
- **Downstream processes (optional):** distribution to retailers, consumer use, and disposal of packaging

The extent of inclusion shall reflect the goal, audience, and decision context. For studies focused on operational or product manufacturing performance, downstream stages may be excluded. However, when materials are exported from a previous production site (e.g., crude fish oil) to omega-3 production site, impacts from shipping (e.g., fuel use, emissions) should be accounted for using relevant data, e.g., transport distance, mode, and emission factors. Source-specific supply-chain related LCA boundaries are described in Section 3: Supply-Chain Specific Guideline.

Figure 2: Generic System Boundary in Process-Based Omega-3 LCAs



- EcoEngineers

2.1.3.4: Cut-off Criteria and Exclusions

Excluding life-cycle stages, processes, inputs, or outputs is only acceptable if it does not significantly affect the study's conclusions. Excluded stages, processes, inputs, or outputs (if any), such as infrastructure or employee commuting, should be justified and documented. The cut-off criteria for initial inclusion of inputs and outputs along with the assumptions underlying these criteria shall be explicitly stated. The criteria selected shall also be assessed and described in the final report. Common criteria for cut-off include:

- **Mass:** Include inputs that contribute more than a defined percentage of the total mass.
- **Energy:** Include inputs contributing significantly to the system's total energy use.
- **Environmental significance:** Include inputs with notable environmental impact, even if their mass or energy contribution is small (ISO 14040/14044:2006).

These criteria should be applied systematically to both inputs and outputs, including emissions and waste. For studies intended for public comparative assertions, a sensitivity analysis must ensure that all significant inputs and outputs, based on mass, energy, and environmental relevance, are included and justified.

2.2: Life Cycle Inventory Analysis

The life cycle inventory (LCI) is the quantitative foundation of the LCA, capturing all relevant inputs and outputs (e.g., materials, energy, emissions, and wastes) associated with an omega-3 product system across its life cycle. LCI results provide the basis for impact assessment and interpretation.

LCI data are drawn from two sources:

- **Foreground data (primary data):** Site-specific data collected from processes directly controlled or influenced by the producer or practitioner, such as fish oil extraction, algae cultivation, or oilseed processing. These data include energy and water use, material inputs, and waste outputs and are typically obtained from facility records, measurements, supplier information, and direct engagement with operators.
- **Background data (secondary data):** Data for upstream and supporting processes not directly controlled by the producer, including electricity generation, transportation, chemicals, packaging, and potentially raw materials (if not controlled by omega-3 producer). This data is obtained from established LCI databases (e.g., ecoinvent, Agri-footprint, USLCI, Sphera), government statistics, industry datasets, and peer-reviewed literature.

All data must be representative of the relevant technology, geography, and the period of the study. Data quality must be evaluated for completeness, consistency, accuracy, and relevance, and any limitations or uncertainties must be documented and addressed in the interpretation phase.

2.2.1: Data Collection Strategy

LCI data should be collected using a structured and transparent approach aligned with the study goal and scope. Data requirements are defined using process flow diagrams and system boundaries, with inputs and outputs mapped to each unit process.

- **Primary data:** This data is used for foreground processes wherever feasible. Standardized data collection templates should be applied to ensure consistency in units, reporting periods, and system definitions. Data may be averaged over representative operating periods and checked using mass and energy balances. Data gaps or anomalies should be resolved through follow-up with data providers or be clearly documented assumptions. Collection of upstream supply-chain data (e.g., raw material

sourcing, fishing practices, transport) is strongly encouraged to improve traceability and support hotspot identification.

- **Secondary data:** This data is used for background processes or where primary data is not available. Dataset selection shall prioritize technological, geographical, and temporal representativeness. When multiple data sets are available, the most representative option should be selected, and the rationale documented. Any modification, scaling, or adaptation of secondary datasets must be transparently reported.

All data shall undergo plausibility and consistency checks before inclusion in the LCA model. Unresolved data gaps shall be addressed using conservative assumptions and documented to support interpretation and review.

2.2.1.1: Data Validation and Uncertainty Management

Data shall be evaluated for temporal, geographical, and technological representativeness. Where data is missing or incomplete, proxies may be used with clear justification (e.g., using a similar oilseed dataset when canola-specific data is unavailable). Key sources of uncertainty and their potential influence on results should be documented and considered in interpretation.

2.2.1.2: Technology Readiness Level or Maturity and Prospective LCA

Omega-3 production processes should be characterized by their level of technological maturity (pilot, demonstration, or commercial). Technology maturity is explicitly considered when defining system boundaries, data quality requirements, and interpretation of LCA results.

Commercial-scale systems typically operate under stable and well-documented conditions and should prioritize primary, site-specific LCI data. In contrast, emerging or pilot-scale technologies often exhibit greater variability in yields, energy demand, and material inputs and may rely on modeled or secondary data; LCAs of such systems should transparently document data gaps, assumptions, and associated uncertainties.

When technologies are undergoing active development (e.g., strain optimization, process redesign, or geographic relocation), inventories should be year-, strain-, and site-specific rather than based on generic datasets. Comparative assertions between technologies at different maturity levels shall be avoided unless differences in data quality, scale, and operational stability are explicitly addressed and tested through sensitivity or scenario analysis.

LCAs of less-mature omega-3 production technologies should be used as directional tools to identify environmental hotspots and improvement opportunities rather than as definitive performance benchmarks. Prospective or scenario-based modeling may be applied to represent plausible future configurations (e.g., renewable energy integration, improved efficiencies, alternative feedstocks) if assumptions are conservative, clearly stated, and distinguished from current operations.

Consistent and transparent treatment of technology maturity is essential to ensure credible interpretation of results and to avoid misrepresentation in comparative assessments or sustainability claims.

2.2.2: Inventory Modelling and Flow Categories

LCI modeling involves systematically compiling and organizing data on all material and energy flows to represent the product system for the chosen functional unit. It acts as a link between the raw data collection phase and the environmental impact assessment in LCA.

This step depends directly on the key elements discussed in the earlier goal and scope phase of an LCA. A modeling tool (such as SimaPro, openLCA, or Sphera, or other process models) can be used to structure, calculate, and link the datasets within the defined system to generate the LCI results efficiently.

Unit process categories typically include:

- Feedstock production and supply (e.g., fishing, aquaculture, algae cultivation, seed farming)
- Harvesting/collection
- Processing (e.g., extraction, purification, concentration)
- Packaging and distribution
- End-of-life (for cradle-to-grave studies)

Flow types captured include:

- Energy (e.g., electricity, fuel)
- Materials (e.g., water, supplementary chemicals, nutrients)
- Emissions (e.g., biogenic and non-biogenic CO₂, nitrogen, phosphorus, etc.)
- Land use
- Waste and by-product management (e.g., composting, anaerobic digestion, animal feed, incineration, landfilling, etc.)

In this guideline, flow types are used to structure the LCI and ensure consistent modeling and impact assessment. Flows shall be classified as:

- Technosphere (product) flows, representing exchanges of materials, products, and intermediates between processes within the modeled system
- Elementary flows, representing exchanges between the system and the environment, including resource inputs (e.g., water, land use, crude oil) and emissions to air, water, and soil
- Energy flows, including electricity, fuels, steam, and heat supplied to or produced by processes
- Waste flows, representing materials leaving a process for treatment, recycling, or disposal

Correct classification of flows is required to ensure proper allocation, impact characterization, and comparability across omega-3 supply chains.

2.2.3: Handling Multiple Products

When a process yields more than one valuable output, it becomes essential to handle multiple products, as they carry different functions. This is one of the critical elements in LCA. In such cases, the environmental burdens associated with the shared process must be appropriately distributed among the co-products to ensure fair and meaningful comparisons. Omega-3 supply chains, regardless of their source, often involve multi-output processes that generate co-products and by-products, such as fishmeal, animal feed, biomass residue, or even pharmaceutical-grade fractions. In such systems, the need for allocation arises when inputs (e.g., energy, raw materials) and emissions cannot be directly assigned to a single product stream.

2.2.3.1: Output Type Definitions

Correct classification of outputs is a prerequisite for selecting an appropriate allocation approach (distribution of environmental impacts across process outputs):

- **Main product:** The primary product is one that motivates operation of the system (e.g., omega-3 oil in dedicated nutraceutical production).
- **Co-product:** A product that is intentionally produced alongside the main product and has economic value and a defined market (e.g., fishmeal, canola meal, residual algal biomass sold as feed).
- **By-product:** A secondary output with limited economic value that is not the primary driver of the system but is nevertheless utilized in other supply chains (e.g., tuna fish head).
- **Waste:** An output that has no intended use and requires treatment or disposal. Waste does not receive upstream environmental burdens unless it is recovered through a waste treatment or valorization pathway.

When a material initially classified as waste is subsequently sold or otherwise generates economic value, it must be reclassified as a by-product or co-product in accordance with ISO 14044 and modeled as a technosphere output subject to allocation or system expansion, rather than as a waste flow. Misclassification of outputs can materially affect results and shall be avoided.

2.2.3.2: Allocation in Multi-Product Systems

The approach for handling the multiple products is generally performed in the following steps:

1. Clearly identify all outputs from the process. These can include identification of the main products (e.g., omega-3), intermediate products of the supply chain (e.g., fish, algae and seed-based refined oil), co-products (e.g., fish meal/oil), or residuals or waste (e.g., wastewater, biomass residues). Understanding the market dynamics for the proper identification of the role of the outputs is essential.
2. Understand the economic and functional relevance of each output, as this is essential for determining how burdens can be shared.

3. Ensure methodological consistency and environmental relevance. This LCA guideline adopts a hierarchical allocation approach, aligned with ISO 14044 and consistent with best practices for complex marine-based and bio-based production systems:
 - **Avoid allocation by adopting the following steps:**
 - **Physical separation/subdivision of processing units:** This approach involves subdivision by attributing energy and material inputs to each product stream where technical and spatial separation (e.g., separate distillation or drying processes for fish oil and fishmeal) is possible. However, it might be challenging in many cases for omega-3 supply chains, as most products across the supply chain share processes, and the approach is data intensive.
 - **System expansion:** When physical separation of the processing units is not applicable, the system should be expanded to include the functions of all co-products, thus accounting the avoided burden of the substituted products. This is known as system expansion or substitution. Most importantly, the system expansion approach first requires careful identification of main and co-products, and then selection of displaced products based on functional equivalence and realistic market responses, rather than deciding only based on one specific functional or market-specific parameters.
 - **If allocation cannot be avoided:**
 - **Physical allocation:** This is required if separation of processing units and system expansion is not feasible. Due to lack of reliable substitution data or when co-products are minor or poorly characterized, impacts can be allocated based on physical relationships such as mass, energy content, or nutrient content, ideally reflecting a causal link between input flows and product generation.
 - **Mass allocation:** Mass-based allocation distributes environmental impacts among products and co-products according to their relative mass. This method is appropriate when products are generated in similar physical forms and when mass reasonably reflects the contribution of each output to the overall process. However, mass-based allocation may be less representative when products differ significantly in function or value. In omega-3 production systems, for example, large-volume outputs such as fishmeal may receive a greater share of impacts than smaller but functionally important products like fish oil or concentrated omega-3 fractions. In such cases, mass-based allocation may not fully capture the functional or economic significance of each product.
 - **Energy allocation:** Energy allocation distributes the environmental impacts among products and co-products based on their calorific value. This method works best when energy is a relevant property, e.g., when multiple products can serve as fuel

or possess energy content. Energy allocation can be appropriate when products carry heating value; in contrast it becomes inappropriate when some co-products are not rich in energy content and are valued mainly for their nutritional or biochemical properties. For example, in fish-based supply chains, fish oil and fish meal contain a significant amount of energy, whereas collagen (from skin and bones) is produced for their protein functionality rather than calories. In algae-based supply chains, algal oil and algae meal carry metabolic energy, but pigments like astaxanthin are valued for antioxidant or coloring properties, not energy content. For oilseed-based supply chains, oil and meals have calorific value, while other fractions of the seed like fibers are produced for health or other functional uses, and not for their energy content. In all these cases, energy allocation would underrepresent these functional co-products, making alternative allocation methods more appropriate. In such cases, allocating impacts solely by energy content can misrepresent the process-product relationship.

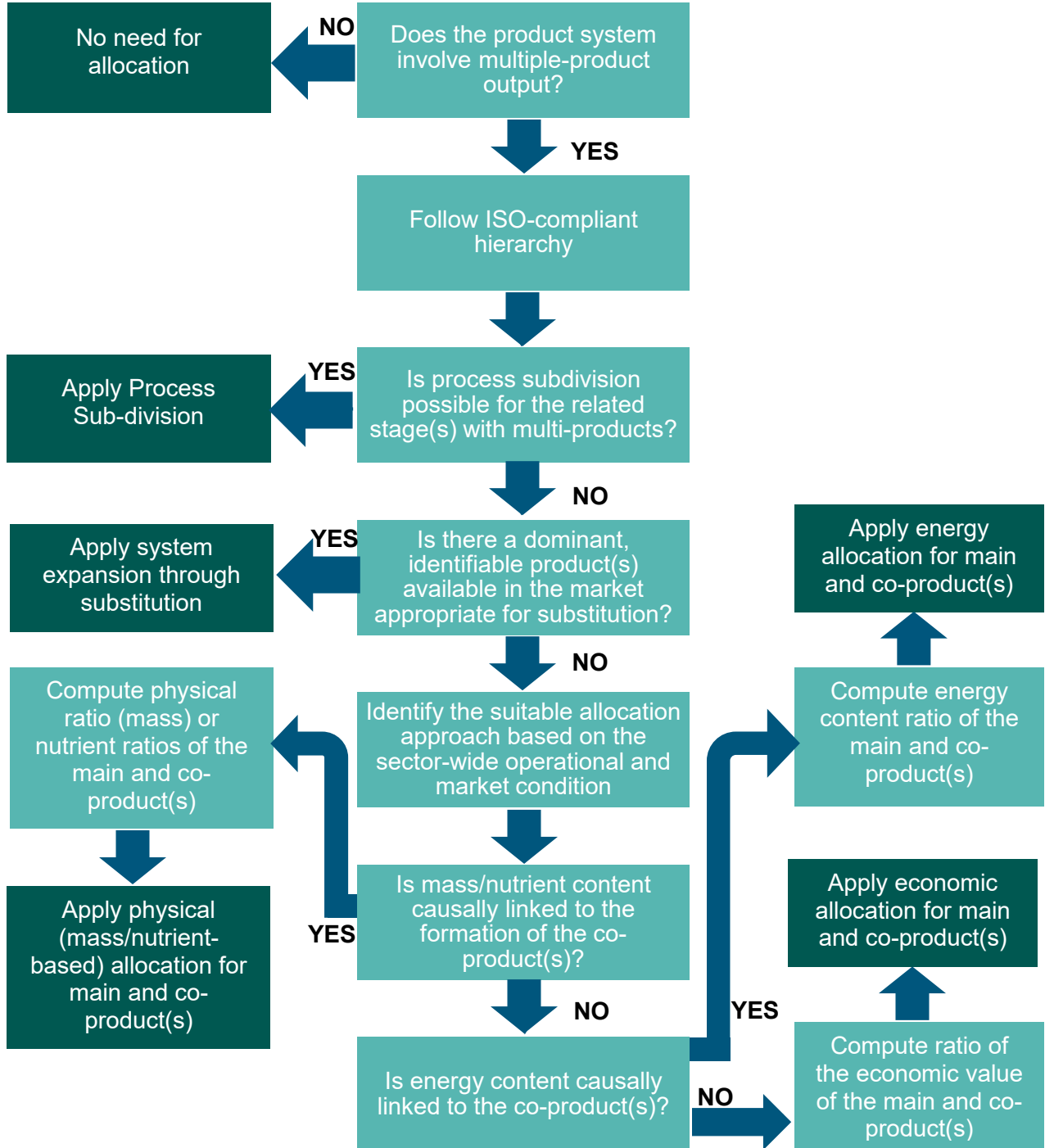
- **Nutrition-based allocation:** Nutrient-based allocation assigns environmental impacts to products and co-products based on their key nutrient contents, such as protein, fat, or specific functional compounds. This method is appropriate when products are valued primarily for their nutritional function, e.g., fishmeal or algae meal for protein, or fish and algal oils for specific fatty acids. This method reflects the functional significance of each product and can provide a more causally representative distribution than energy- or mass-based allocation, especially when other non-nutrient properties are not relevant.
- **Economic allocation:** Alternatively, when physical relationships do not sufficiently represent value generation, burdens can be distributed based on the market value of each co-product. This method reflects economic and functional significance (e.g., nutrient composition) but may introduce variability due to price fluctuations.

All approaches discussed are acceptable under ISO 14044, provided the selected method is applied consistently across the supply-chain modeling, the rationale is well-documented, and sensitivity analysis of the allocation approach is conducted where allocation materially influences results, especially for the economic allocation, as this approach is vulnerable to the market dynamics and price fluctuations of the co-products. A sensitivity analysis of the market prices ensures the results are robust, transparent, and not influenced by temporary or region-specific market conditions. To ensure representativeness and alignment with data quality requirements, practitioners should consider using multi-year average prices to represent the price volatility or when recent price signals are critical (e.g., a 3-10-year rolling average). The selected price timeframe should be transparently reported, and sensitivity analysis is recommended due to the known sensitivity of economic allocation results to price variability (Guinée et al., 2004; Ardente et al., 2012; Parajuli et al., 2017).

The choice of allocation method shall be applied consistently across all relevant multifunctional processes within the system boundary. Mixing allocation approaches (e.g., applying system expansion in some cases and economic allocation in others for comparable co-product situations) should be avoided. Consistency is essential to preserve internal coherence and methodological integrity.

The allocation hierarchy explained in this section is further illustrated in a simplified decision tree in Figure 3. It should be noted that for certain market applications (e.g., aquaculture feed, pet food, or other animal nutrition products), particularly where product declarations or labeling are intended, relevant established Product Category Rules (PCRs), including Product Environmental Footprint Category Rules (PEFCRs), may prescribe specific allocation approaches. In such cases, these requirements may be followed to ensure consistency and comparability within the relevant product category and market context. For example, guidance developed under organizations such as the European Pet Food Industry Federation (FEDIAF) for pet food (FEDIAF, 2025), or PEFCRs for animal feed used in aquaculture (FEFAC, 2025), define consistent methodological choices to ensure comparability of cradle-to-gate results across business-to-business supply chains. In the absence of applicable PCR or PEFCR, or for assessments intended for broader analytical or decision-making purposes, the decision tree outlined in this study should be applied to select an appropriate allocation or system expansion approach, which aligns with relevant LCA standards.

Figure 3: Decision Tree for Handling Multiple Products in Omega-3 LCAs



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Table 2-A discusses an example where an allocation decision might be required along the supply chain of fish-based omega-3 production, and how the decision could be treated following the hierarchy guidelines discussed in this section (2.2.3.2. Allocation in Multi-Product Systems).

Table 2-A: Illustrative Example for Applying Allocation Guideline for Omega-3 Systems with Multiple Product Systems

Allocation procedure for fish-based omega-3 production

- 4. Physical separation/subdivision:** For fish-based omega-3, applying physical separation will have limitations because process subdivision would require attributing energy and material inputs to each product stream. However, in upstream processes of this supply chain, including the fish processing step, the same raw fish input simultaneously produces multiple outputs, while sharing energy input and infrastructure, making such subdivision infeasible.
- 5. System expansion:** Fishmeal is widely used as an ingredient in animal and aquaculture feed systems. However, how this co-product is treated in an allocation procedure will be largely dependent on the market it is entering. For example, fishmeal may be considered as a potential substitute for plant-based protein meals, such as soybean meal, particularly in pet food or livestock feed markets where both serve as protein sources. This approach is relevant because plant-based protein, particularly soybean meals, have a larger supply, lower price, and higher market share compared to fishmeal in the pet food or livestock feed market sector.

However, system expansion may be challenging if co-products already dominate their functional market or serve niche markets. For example, fishmeal is a dominant product in high-value aquaculture feeds (e.g., salmon farming). System expansion relies on the substitution of a marginal or average product mix available in the market; if no clear displaced product can be identified, its application becomes more complex.

As the feed sector evolves, and if alternative feed ingredients, such as insect meals, microbial proteins or other novel protein sources, become increasingly more viable for aquaculture, poultry, and livestock than fishmeal, the allocation approach might need to be revisited. By considering these substitution options and their nutritional equivalence at the margin, system expansion can still be applied to account for the environmental impacts avoided by using fishmeal instead of alternative feed ingredients.

Where fishmeal is not the dominant product in the market and may serve as a substitute for multiple products (e.g., pet food), conducting a sensitivity analysis can help quantify how the choice of benchmark for substitution influences the overall environmental impact of the system.

The same principle applies to co-products targeting niche or emerging markets. For example, if a co-product from marine oil extraction could enter the pigment market, system expansion is less appropriate if the market is not well-established, lacks clear functionality, or faces no direct competition.

6. Physical allocation:

- a. **Mass allocation:** mass allocation can theoretically be applied; however, it will have limited applicability. For example, in early rendering stages, allocating impacts by mass may undervalue high-value omega-3 products and fail to reflect their functional importance.
- b. **Energy allocation:** energy allocation can be applied based on the calorific value of process outputs. However, omega-3 products are primarily produced for nutritional or pharmaceutical purposes, not for energy purposes. As a result, allocation by energy may not capture the true causal relationships in the system.
- c. **Nutrition-based allocation:** In fish-based omega-3 supply chains, nutrient-ratio-based allocation approach can help to assign environmental burdens based on key nutritional contributions, such as protein in fishmeal and EPA/DHA in omega-3 concentrates. An advantage of using this approach is that it can reflect the functional value of each product and co-product, giving omega-3 products appropriate weight in the LCA; it can be implemented using nutrient indices or standardized serving sizes. However, as disadvantages, it requires detailed nutrient composition data, which may be sensitive to the choice of nutrients included, and can be complex to apply when co-products have multiple nutritional roles or when comparing across different markets. For example, this method can be applied for allocating between functional oil and feed products; however, doing so would allocate most impacts to fishmeal and fewer to fish oil as fishmeal contains most of the protein and mass fraction. If the allocation is being done on a fatty acid content basis, the burden of the impacts between the co-products might completely shift, depending on their fatty acid content.

Physical allocation may work in early rendering stages, but may become less meaningful for high-value refined products.

7. **Economic allocation:** economic allocation can be applied to the omega-3 production supply chain because product values often differ significantly among co-products. Omega-3 concentrates typically represent the highest-value output and frequently drive the economic motivation for fish oil processing and refining. Allocating environmental burdens according to the relative market value of each product can therefore better reflect the underlying drivers of production. For example, in the case of a tuna fish-based supply chain, the driving economic factor can be the non-head portion of the fish, which is targeted for food market, while the head can be processed to produce omega-3 products. Here, applying economic allocation might be more relevant when there is no partitioned data between the head and remaining body used in the respective market, and the point of allocation applicable at the sorting stage.

However, economic allocation has limitations, including sensitivity to price fluctuations caused by variations in fish catch volumes, aquaculture demand, nutraceutical markets, and global commodity prices. For this reason, a sensitivity analysis should be conducted to ensure that the allocation results are robust under different market conditions.

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Fish species differ substantially in lipid distribution and commercial value, which influence how outputs are classified within the product system. The examples presented in Table 2-A illustrate that the classification of outputs as main products, co-products, or residuals depends on species-specific lipid distribution and market context. As by-products increasingly contribute to fish oil and fishmeal production, their treatment in LCA models reflect their functional role and economic relevance rather than being assumed as waste.

2.2.4: Data Quality Assessment

Data quality indicators (DQIs) in LCA are essential for evaluating the reliability, representativeness, and transparency of data used in environmental impact studies (ISO 14040/44:2006). They help practitioners assess whether datasets accurately reflect real-world processes across various dimensions such as technology, geography, and time. Common DQIs are listed below.

- Technological representativeness (i.e., how well the data reflects actual production technology)
- Geographical representativeness (i.e., alignment with regional conditions)
- Temporal representativeness (i.e., data age and relevance)
- Completeness (i.e., coverage of all relevant flows and processes)
- Precision/uncertainty (i.e., variability and confidence in measurements)
- Consistency (i.e., methodological coherence across datasets)
- Transparency/documentation (i.e., clarity and accessibility of underlying assumptions and sources)

High-quality data ensures robust LCA results, enabling credible comparisons and informed decision-making.

Tentative data quality attributes relevant to omega-3 supply chains are shown in Table 2-B. Depending on the types of feedstocks used in the omega-3 production, the LCI, source of data, quality of data, and the potential uncertainties due to such can vary. Classifying variability as high, medium, or low for each DQI is crucial because it transforms qualitative assessments, which can be derived from the pedigree matrix (Ciroth et al., 2016) into actionable insights. For example, while using the ecoinvent database, the pedigree matrix is used as a simple scoring system to evaluate and document data quality by rating how reliable and representative a dataset is. It is mainly based on key aspects such as reliability, completeness, temporal, geographical, and technological representativeness, helping users understand the uncertainty and robustness of the data used in an LCA. This categorization improves comparability across systems, supports uncertainty analysis, and helps prioritize data improvement efforts. For example, high variability signals the need for sensitivity testing or scenario modeling, while low variability suggests stable and reliable datasets. It also enhances transparency for stakeholders and aligns with ISO and European Normalization (EN) standards, which encourage structured reporting of data quality. Ultimately, this approach ensures clearer communication and more robust decision-making in LCA studies.

Table 2-B: Potential Data Quality Indicators and Source of Variability

Data Quality Indicator	Fish-based Omega-3 Source of Variability	Algae-based Omega-3 Source of Variability	Oilseed-based Omega-3 Source of Variability
Technological Representativeness	Variances include fishery type, oil extraction technology, and traditional boats vs. modern vessels.	Datasets from pilot vs. industrial-scale operations vary	Agricultural practices and processing technologies; requires better agroecological representation.
Geographical Representativeness	Marine catch regions (e.g., Atlantic vs. Pacific) have different energy mixes and species.	Production is often generically modeled; regional effects (sunlight, CO ₂ availability) underrepresented in yield and operations	Farming practices vary by region and availability of regional agricultural datasets across various geographies.
Temporal Representativeness	New data limitations; older datasets may not reflect current fuel efficiency or seasonal sustainable fishing quotas	Rapid technological change means data become outdated quickly	Periodic agricultural data updates or census (e.g., FAOSTAT, ecoinvent, USDA, and other country/region specific data) are, however, not necessarily spatially explicit
Completeness and Reliability	Product(s) (e.g., fish meal, fish oil, protein fractions) often not fully included or allocated	Nutrient recycling, CO ₂ sourcing, and water reuse are often missing	Full process chain often not included, from cultivation to processing for end-products
Precision / Uncertainty	Catch size, species, and energy use	Lab-to-pilot scale results have large uncertainty ranges	Field or measured data are consistent and well quantified representing the agroecology
Consistency	Allocation methods vary (e.g., mass,	Boundary definitions differ	There is a lack of standardized LCA

Data Quality Indicator	Fish-based Omega-3 Source of Variability	Algae-based Omega-3 Source of Variability	Oilseed-based Omega-3 Source of Variability
	economic, energy basis)	between studies. Allocation methods also vary	methodologies applied for different crop systems. Allocation methods also vary
Transparency / Documentation	Verified chain-of-custody documentation not available for all of the catch, especially for small-scale fisheries	There is limited disclosure of proprietary lab-scale conditions as well as industrial processes	Detailed reporting from agricultural databases (especially more for larger farmers than smallholder farms) and industry studies might be available

- ISO 14044, 2006 ; Davis et al., 2021; McKuin et al., 2023, Zhang et al., 2021 ; Togarcheti & Padamati, 2021 ; Schade et al. 2020 ; Ukaew et al., 2016 ; Pelletier et al., 2008

2.3: Life Cycle Impact Assessment

The LCIA phase provides the basis for identifying the environmental hotspots, comparing alternative omega-3 supply chains, and calculating in-process improvement strategies. LCIA translates LCI results into potential environmental impacts through a structured set of mandatory and optional elements. Mandatory elements of LCIA consist of:

- Selection of impact categories
- Classification, which involves assigning LCI results to the relevant impact categories (e.g., CO₂ and methane, CH₄, are classified as contributors to climate change)
- Characterization (e.g., global warming potential or GWP over 20-, 100-, or 500-year time horizon), which quantifies the contribution of each LCI result to its respective impact category using characterization factors (e.g., converting all greenhouse gases, GHGs, into carbon dioxide equivalents, CO₂e)

Optional elements, while not required for an ISO-compliant LCA, may be applied to support further interpretation of results. These elements can include normalization, weighting, and data quality or uncertainty analysis. Because these steps involve additional assumptions and methodological choices, their results are subject to higher uncertainty and should be interpreted with caution.

2.3.1: Selection of Impact Categories

The selection of life cycle environmental impact categories is guided by core principles and requirements defined in ISO 14044:2006. The selection of the categories shall be directly relevant to the goal and scope of the study, ensuring that they capture the most significant environmental effects associated with the product system.

The selection should be sufficiently complete to address all important environmental concerns while avoiding unnecessary overlap or double counting. Each category must be based on scientifically valid cause-and-effect relationships between LCI flows and potential environmental impacts. For example, GHG emissions from fishing vessels, algae cultivation, and canola farming contribute to climate change; fertilizer runoff from canola or algae systems causes eutrophication; and fuel use in fishing or processing leads to resource depletion. Considering these drivers, it is important that specific field emissions and methods used to quantify those are applied consistently and transparently. The relevance of specific categories may also vary by supply chain. For instance, marine ecotoxicity and impacts on aquatic ecosystems are particularly relevant for fish- and krill-based omega-3, whereas land use- and eutrophication-related impacts are more relevant for canola-based systems.

Transparency is essential in documenting the rationale for including or excluding certain impact categories. This includes justification for the inclusion of marine impacts for fish-based systems, energy demand for algae cultivation, or land use and nutrient emissions in agricultural systems. Finally, the selected categories must be consistent with the modeling framework used in the LCA, whether focusing on midpoint indicators (e.g., global warming potential) or endpoint indicators (e.g., ecosystem quality). Midpoint indicators represent cause-and-effect relationships at an intermediate stage of the environmental impact pathway, whereas endpoint indicators aggregate these effects into broader damage categories. As a result, midpoint indicators rely less on value judgments and aggregation assumptions. Their use improves transparency, reproducibility, and comparability across studies and LCIA methods and allows results to be more directly linked to inventory data and potential mitigation measures. While midpoint indicators generally provide higher scientific robustness, endpoint indicators can be easier for decision-makers to interpret, though they carry greater uncertainty.

Applying these principles ensures that the LCA of omega-3 derived from fish and krill, algae, and canola provides a balanced, scientifically robust, and transparent comparison of their environmental trade-offs.

The below impact categories highlighted in this LCA guideline are indicative and may vary depending on the selected LCIA method, characterization models, and category indicators. Commonly used midpoint impact categories include, but are not limited to, the following:

- Climate change (GWP100, GWP20 where relevant to short-lived climate forces)
- Water use or water scarcity
- Land use
- Eutrophication (e.g., freshwater, marine, terrestrial)
- Acidification
- Human toxicity (cancer and non-cancer effects)

- Ecotoxicity (e.g., freshwater, marine, terrestrial)
- Resource use and depletion (fossil and mineral resources)

Optional or supplementary considerations (encouraged where relevant to the goal and scope):

- Biodiversity-related indicators (fisheries biotic resource depletion and seabed impact)
- Selected socio-economic indicators (outside of this ISO-LCA core scope)

In this guideline, midpoint impact indicators are used as the primary basis for impact assessment because they are more closely linked to life cycle inventory flows and are therefore associated with lower uncertainty than endpoint indicators.

Endpoint indicators may be reported in addition to midpoint results where appropriate, but they are not required to meet the core objectives of this guideline. Where included, endpoint impact categories typically address damage to human health, ecosystems (biodiversity and ecosystem quality), and natural resources or resource availability. It should be noted that not all LCIA methods support the calculation of endpoint indicators.

The final selection of impact categories, indicators, and time horizons will be consistent with the chosen LCIA method and the goal and scope of the study. Section 3: Supply-Chain Specific Guideline provides guidelines for consideration and selection of the impact categories.

2.3.2: Selection of LCIA Methods

LCIA methods differ in their underlying models, impact category coverage, characterization factors, spatial differentiation, and temporal assumptions. These methodological differences can significantly influence the outcomes of an LCA study. Explicitly justifying the selection must be done to ensure alignment with the study's goal and scope (e.g., global vs. regional impacts), ensure comparability across studies or products, support credibility in decision-making, reporting, and public communication, and clarify limitations and assumptions inherent in the chosen method.

The selection of an LCIA method should be scientifically valid, consistent with the chosen impact categories, and appropriate for the geographical and temporal context. For example, comparing omega-3 production from fish and krill, algae, and canola requires methods that cover key impacts like climate change, eutrophication, and resource depletion. Specialized models such as the USEtox model (Rosenbaum et al., 2008) may be applied for toxicity-specific impact pathways where appropriate. Regional relevance is an important consideration, too. Methods such as the U.S. Environmental Protection Agency's Tool for Reduction and Assessment of Chemicals and other Environmental Impacts, or TRACI, (Bare, 2002) are mainly designed for North America, while ReCiPe (Huijbregts et al., 2016) or Environmental Footprint (EF) (European Commission, 2021) provide broader global or regionally differentiated coverage. For studies focusing primarily on climate change impacts, the IPCC 2021 LCIA method may be applied using updated characterization factors for various GHGs (IPCC, 2021).

Data compatibility between the LCI database, the selected LCIA method, and the software is crucial. Additionally, the choice should match whether midpoint (e.g., GWP, acidification) or endpoint (e.g., human health, ecosystem quality) indicators are needed, as all the LCIA methods do not necessarily calculate the impact at both midpoint and endpoint levels. As stated

earlier, midpoint indicators represent environmental impacts at an intermediate stage of the cause-effect chain, focusing on a specific environmental mechanism before it causes final damage (e.g., GWP, acidification potential, eutrophication potential, ozone depletion). Endpoint indicators represent the final aggregated damage caused by environmental impacts to areas of protection such as human health, ecosystem quality, and resource availability (Huijbregts et al., 2016; Margni et al., 2008).

Transparency in the selection of LCIA method is essential. The reasons for selecting an LCIA method, its strengths, limitations, relevance, and regional applicability shall be clearly documented. For comparative LCAs, the same LCIA method and characterization factors should be applied consistently across all supply chains evaluated to ensure comparability.

2.4: Interpretation

The interpretation and data quality components of the omega-3 LCA methodology ensure that results are credible, transparent, and actionable. Interpretation integrates LCIA results with data quality considerations to identify significant issues, evaluate the robustness of conclusions, and derive meaningful insights that allow fair comparison across omega-3 sources while supporting continuous improvement within the industry.

2.4.1: Identification of Significant Issues

A systematic review of LCIA results should be applied to identify the primary drivers to the evaluated environmental indicators, including:

- Hotspot analysis, which determines key contributors to environmental impacts (e.g., dominant drivers of carbon intensity, energy use, or nutrient emissions)
- Assessment of data quality, completeness, and representativeness for key processes and supply chain stages, which determines the credibility and reproducibility of LCA studies

This step supports the identification of processes, inputs, or life-cycle stages that have the greatest influence on overall results and can suggest the areas where improvement efforts may be most effective.

2.4.2: Evaluation

The robustness of LCIA results should be evaluated through the following:

- **Sensitivity analysis** assesses the influence of key assumptions, methodological choices, and data gaps on study outcomes.
 - Sensitivity analysis shall be conducted for parameters likely to influence results, including allocation, system boundaries, energy mix, yields, efficiencies, transportation distances, and key upstream inputs (e.g., fuel, sugar, fertilizer).
- **Uncertainty analysis** (quantitative or qualitative) should be conducted, where appropriate, to characterize the confidence in results arising from input data variability and modeling assumptions.

- **Scenario analysis** may be conducted to explore alternative, future or emerging production pathways, technological developments, or sustainability initiatives (e.g., renewable energy integration into processing facilities, waste valorization) relevant to omega-3 supply chains.
- **Consistency and completeness checks** should be conducted to ensure alignment with the defined goal and scope, methodological choices, and data requirements.

These evaluations help determine whether conclusions are stable under reasonable variations in assumptions and whether comparisons across omega-3 sources are reliable.

2.4.3: Conclusions and Recommendations

Based on the interpretation of results, conclusions must be drawn aligning with the goal and scope of the study and supported by the underlying analysis. This includes:

- Summary of key findings for each omega-3 source (e.g., fish and krill-, algae-, and oilseed-based systems)
- Identification of improvement opportunities and mitigation strategies targeting significant impact drivers
- Guidance on the appropriate use of results for comparison, communication, or decision-making, including any conditions or limitations affecting comparability

Recommendations should be framed to support continuous improvement rather than prescriptive claims beyond the study's scope.

Reporting and Limitations

The LCA interpretation should be fully and transparently documented to allow readers to understand the results, assumptions, and limitations of the study. Key limitations should be explicitly stated, including:

- The modeling of potential environmental impacts rather than actual, site-specific impacts
- Limited spatial or temporal resolution for certain impact categories
- The influence of methodological choices and assumptions (e.g., allocation procedures, proxy data, or scenario definitions) on results

Clear communication of these limitations is essential to prevent misinterpretation and ensure responsible use of the LCA findings.

Section 3: Supply-Chain Specific Guideline

This section provides step-by-step LCA and specific impact categories for marine animal-based, algae-based, and oilseed-based omega-3 productions.

3.1: Marine Animal-Based Omega-3

Marine animal-based omega-3 oils are derived from wild-harvested or aquaculture-associated marine organisms and are inherently linked to marine ecosystems. This section defines supply-chain characteristics and impact drivers that are specific to marine animal systems including fish (e.g., anchovy, tuna, pollock) and krill and that require differentiated treatment compared to the plant- and microbial-based pathways, supplementing the general methodological guidance in Section 2: Fundamentals of Life Cycle Assessment.

Fish and krill are discussed together in this section due to structural similarities in their supply chains; however, differences in harvesting conditions, processing practices, yields, and ecosystem roles can materially result with different environmental profiles (Parker et al., 2012). These differences are addressed in sections 3.1.3: Fish-Based Omega-3 and 3.1.4: Krill-Based Omega-3.

3.1.1: System Boundary

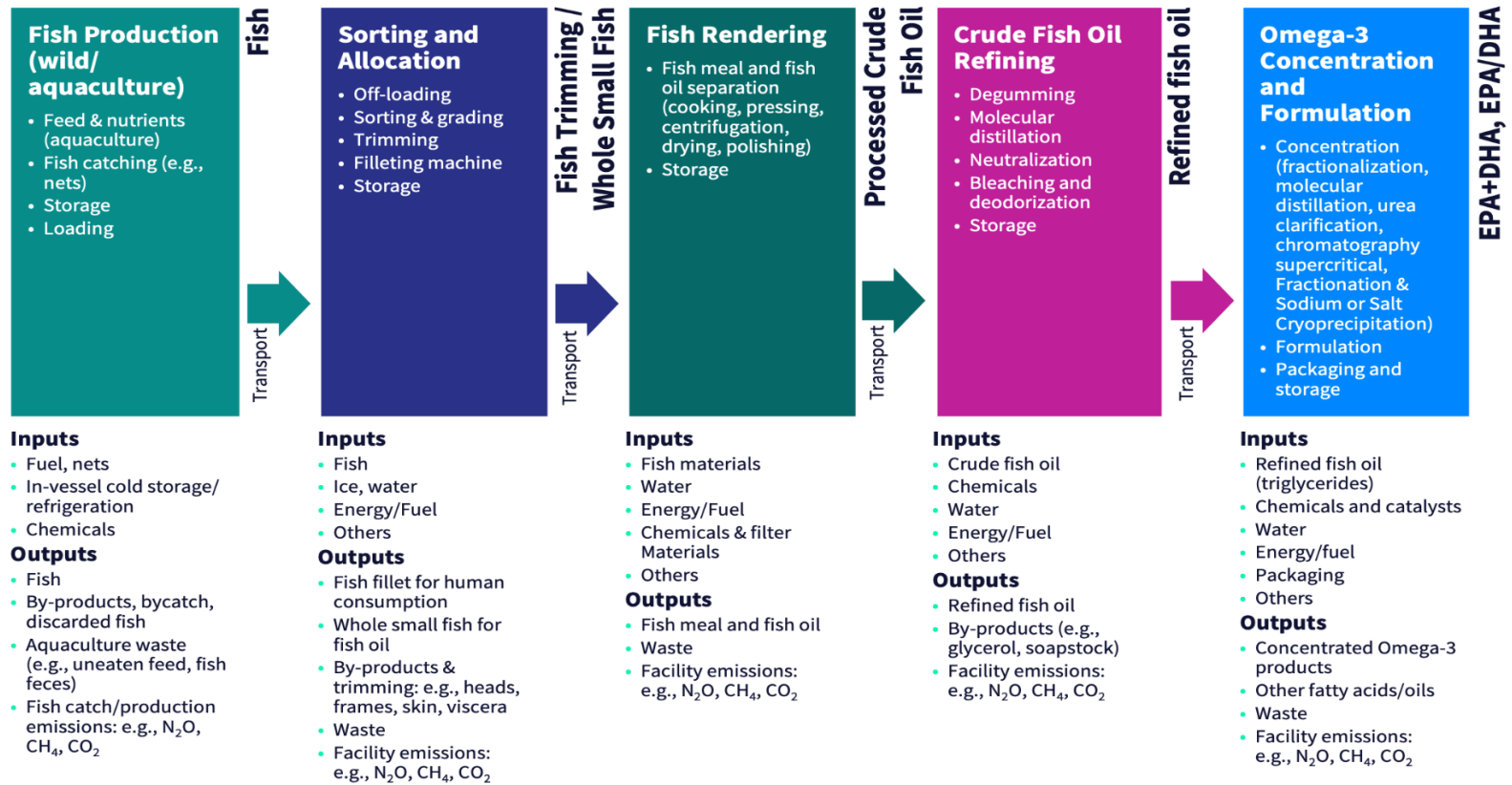
A cradle-to-gate system boundary for marine animal-based omega-3 LCAs typically encompasses the following stages (Bashiri et al., 2024; Hilmarsdóttir, 2022; Newton et al., 2023; Schade et al., 2020):

- Raw material acquisition (e.g., capture fisheries or aquaculture harvesting)
- Primary processing and rendering
- Oil extraction, refining, and stabilization
- Omega-3 enrichment, concentration, packaging and storage (as applicable).

The declared product shall reflect the modeled output (e.g., crude oil, refined oil, EPA/DHA content). Figure 4 presents a high-level block flow diagram of the supply chain for fish-based omega-3 production. Individual stages, with some relevant activities, are shown, however these stages may be performed or owned by different entities along the value chain. While a block flow diagram for krill-based omega-3 production may appear similar at this high level, the underlying environmental impacts can differ substantially due to differences in input requirements, process efficiencies, logistics, and the ecosystems in which these systems operate. Aquaculture-derived inputs shall be clearly distinguished from wild-capture systems, as they are governed by fundamentally different environmental drivers, risk profiles, and improvement pathways. Where by-products from wild capture or aquaculture (e.g., trimmings or offal) are used as feedstocks for omega-3 production, the classification of these materials as co-products, by-products, or waste shall follow the guidance provided in Section 2.2.3.1: Output Type Definitions. The corresponding allocation approach shall then be applied in accordance with 2.2.3.2: Handling Multiple Products.

Figure 4: Schematic Cradle-to-Gate System Boundary for Fish-Based Omega-3 Supply Chain

Each stage of omega-3 supply chain may not necessarily be operated by a single entity.



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- Informed by (Bartek, et al., 2021; Bashiri et al., 2024; Cantillo, et al., 2025; Newton, et al., 2023; Parker et al., 2012; Schade, et al., 2020, Togarcheti, et al., 2021; Zhang, et al., 2021)

3.1.2: Wild Capture vs. Aquaculture-Derived Inputs and Impacts

Wild capture (catch) involves hunting and harvesting fish from natural aquatic ecosystems (e.g., oceans, lakes, rivers). This process focuses on locating, catching, and preserving fish, utilizing fishing vessels, nets, and traps. Aquaculture on the other hand involves raising fish under controlled conditions, including stocking, feeding (e.g., fishmeal, fish oil, plant protein), and water quality management. Therefore, wild capture systems are driven primarily by fuel use, catch efficiency, and stock dynamics, whereas aquaculture-derived inputs depend on feed production and conversion rate, energy (e.g., aeration) and water use, and farm-level management including waste cleanup and treatment. These systems shall not be aggregated without justification, as impact drivers and improvement opportunities differ substantially.

While the following Sections 3.1.3 and 3.1.4 mainly describe the wild catch processes, the principles could potentially be applied to aquaculture as well.

3.1.3: Fish-Based Omega-3

Fish-based omega-3 production is a technically mature industry with relatively well-established fishing, rendering, and refining processes. Primary data availability is generally strong for large industrial fisheries, though smaller or artisanal operations may exhibit greater variability.

Key environmental drivers for this supply chain (Deville, et al., 2025) include:

- Fuel consumption during fishing, which can vary widely per fish stock caught based on stock location, vessel size, and fishing method
- Catch efficiency and seasonality, which affect both catch effort and omega-3 yield (e.g., due to the type of species caught), influencing energy and material requirements during processing
- Co-product handling (fish oil and fishmeal), see section 2.2.3.2: Handling Multiple Products, Table 3-A, and Figure 5
- Long-distance transport and storage, particularly for refrigerated or export-oriented supply chains, e.g., fish or fish oil

Marine ecosystem pressures (e.g., stock depletion, bycatch, habitat disturbance) are not fully captured by standard LCIA methods. Where relevant, complementary indicators or scenario analyses should be applied to support interpretation.

3.1.4: Krill-Based Omega-3

Krill-based omega-3 production shares several system characteristics with fish-based omega-3 supply chains; however, it presents distinct methodological challenges due to its ecological context, geographic remoteness, and biological properties.

Krill is typically harvested in highly sensitive marine ecosystems, often under stringent international management regimes. Krill fisheries are also frequently located in remote regions (e.g., Antarctic waters), in contrast to many fish fisheries that operate closer to shore and to regional processing facilities. While fish can be processed at larger scale centralized facilities, krill undergo rapid enzymatic degradation and therefore must be processed shortly after harvest, often on board the fishing vessel. This reduces storage time but increases on-site

energy demand. Fish, by comparison, can tolerate longer storage and transport times due to larger batch volumes and more established logistics. As a result, krill harvesting can be substantially more energy-intensive with higher fuel use per unit of catch due to longer vessel travel distances, extended time at sea, and more energy-demanding cold-chain requirements (Parker et al., 2012; Newton et al., 2023).

Differences in stock dynamics, lipid content (and therefore omega-3 yield), and the central ecological role of krill within marine food webs introduce additional impact pathways and elevate biodiversity and ecosystem considerations. Furthermore, krill processing may generate fewer or lower-value co-products compared to many fish-based systems, which can influence allocation choices and overall life-cycle results.

Key environmental drivers for this supply chain that should be explicitly documented include:

- Harvest region and fishery management framework
- Stock status and reference points
- Fuel use intensity and transport distances
- Cold-chain and onboard processing requirements
- Co-product and by-product handling and allocation approach

Marine ecosystem sensitivity and biodiversity risks should be transparently addressed, and limitations related to data availability and ecological uncertainty should be clearly reported.

Table 3-A: Examples of Multi-Product Systems within Marine Animal-Based Oil and Omega-3 Production Supply Chains Requiring Allocation Handling

Small pelagic fish (e.g., anchovy, sardine, herring, menhaden) are typically harvested whole for fishmeal and fish oil, as their lipid content is distributed throughout the body. In these systems, both oil and meal are generally considered main co-products.

Large food fish (e.g., tuna, salmon) are primarily harvested for human consumption as fillets. Heads, frames, viscera, and trimmings are generated as by-products and may be further processed into fish oil or fishmeal. These streams represent secondary products that retain economic and functional value.

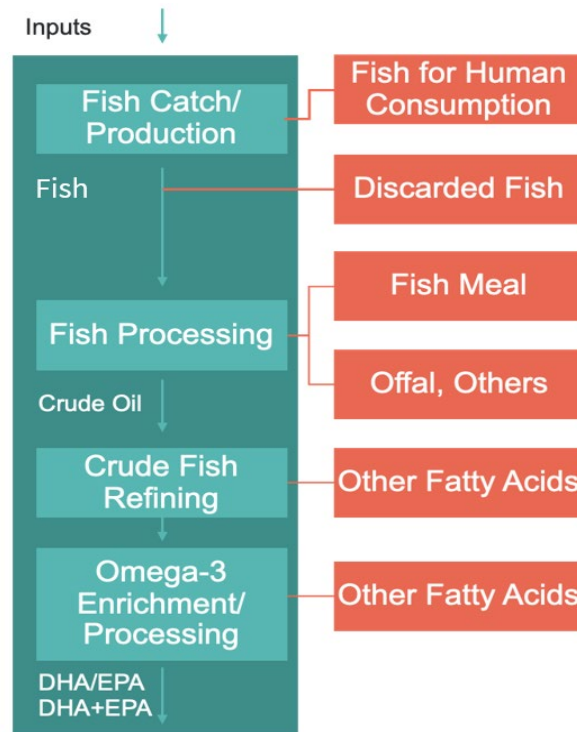
Lean species (e.g., cod) are primarily harvested for human consumption. They contain limited fat in the muscle tissue; oil is therefore extracted mainly from the liver (cod liver oil), while remaining tissues are typically processed into fishmeal or other secondary products.

Roe and body of fish (e.g., salmon) from aquaculture primarily produced to provide salmon fillets or steaks for human consumption, share upstream processes.

Krill processing residual solids, whilst a by-product of oil production (the primary reason for harvest), can be applied as organic fertilizer, offering a sustainable, nutrient-rich alternative that can credit against, or replace, the production of synthetic fertilizers.

- NOAA Fisheries, FAO, 1986, 2011; Kristinsson, 2010; Bimbo, 2000, 2019

Figure 5: Potential Allocation Points for Fish-Based Omega-3 Production



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3.1.5: Methodological and Environmental Challenges

Marine animal-based omega-3 systems present distinct methodological challenges driven by high operational variability, complex co-product structures, and limited data transparency. Fuel use is typically the dominant contributor to impacts, yet varies widely across fisheries, making generic datasets unreliable. Primary, fishery-specific data is therefore essential.

Key challenges include:

- High variability in fuel intensity due to differences in species, gear type, vessel size, fishing grounds, and stock conditions
- Complex co-product systems (e.g., fish oil, fishmeal, by-products of wild catch vs aquaculture), where allocation choices strongly influence results and must be consistently applied and justified
- Energy-intensive cold-chain logistics, including onboard processing, refrigerated storage, and long-distance transport, which are often underreported
- Seasonal and geographic variability affecting catch efficiency, yields, and logistics, requiring sensitivity analysis to ensure robustness

3.1.6: Relevant Impact Categories

The following impact categories are of heightened relevance for marine animal-based omega-3 systems due to dominant emission pathways:

- Climate change (driven by fuel use)
- Marine eutrophication and ecotoxicity (i.e., processing effluents or accidental discharges)
- Resource use (e.g., fossil fuels)
- Marine acidification related to fuel use driven by CO₂ and SO₂ emissions from vessel fuel use, contributing to marine ecosystem stress

Table 3-B provides additional details on impact categories relevant to marine-animal supply chain of omega-3 production and the contributing indicators.

Table 3-B: Major Impact Categories for Evaluating LCI of Marine Animal-Based Omega-3 Product(s)

Impact Category*	Relevance Based on Emissions from Corresponding Stages of the Supply Chain
Climate Change	Vessel fuel combustion during fishing, electricity and thermal energy for rendering, oil refining, concentration, and refrigerated storage
Eutrophication	Nutrient-rich wastewater from fish processing and rendering; discharge water from cleaning and effluent treatment systems
Acidification	SO ₂ and NO _x emissions from marine fuel combustion in fishing vessels and long-distance transport
Water Use	Cleaning, processing, and rendering operations; cooling water for refining and concentration
Resource Use	Fossil fuel use in fishing fleets; electricity and thermal energy in oil extraction, refining, and cold storage
Photochemical Ozone Formation	NO _x and volatile organic compound (VOC) emissions from vessel engines, transport vehicles, and solvent use in refining
Human Toxicity and Ecotoxicity	Accidental fuel spills, solvent losses, wastewater discharges, and antifouling agents on vessels
Ozone Depletion	Leakage of refrigerants from cold storage, transport containers, and processing facilities

*Impact categories are indicative only. Most LCIA frameworks do not yet include marine biodiversity and long-term supply of fish impact categories such as overfishing.

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3.1.6.1: Biodiversity and Stock Depletion Indicators

Where stock depletion or biodiversity impacts are material, it is encouraged that indicators be applied to quantify ecological risk. Two recognized approaches are recommended:

1. Distance-to-Target (DtT) method (Bach et al., 2022)

- Compares the current status of a fish or krill stock to a defined safe limit or target.
- The distance to the target is used to calculate characterization factors for LCIA.

2. Ecological Scarcity 2021 (Frischknecht, 2009; Frischknecht et al., 2021)

- Provides eco-factors for marine species by integrating annual catch, current stock biomass, and intrinsic growth rates.
- Impacts are expressed per mass of fish caught and can be converted to the functional unit (e.g., per gram EPA+DHA).

LCA practitioners should select the method best suited to the available data; both approaches may be applied in sensitivity analyses. Stock status, fishery source, and ecological uncertainty should be reported alongside LCIA results. For krill, their central ecological role and management regime should be explicitly accounted for. Characterization factors shall be transparent, traceable, and linked to the functional unit to ensure comparability across omega-3 sources. This mid-point assessment contributes to the “natural resources” area of protection, allowing fisheries to be compared based on depleted stock fractions. Characterization factors are derived using a marginal approach that integrates catch data, current biomass, and maximum growth rates to represent stock dynamics.

While these indicators can help with evaluating the biodiversity impact of marine animal-based supply chains, when cross-ecosystem (marine, freshwater, terrestrial) biodiversity impact comparison is needed, a combined end-point biodiversity framework might be better suited. Such endpoint aggregation methods are still in development and could improve the ability to capture cumulative biodiversity damage and allow consistent comparison of impacts across ecosystems (Brown et al., 2025; Hélias, 2025).

3.1.7: Summary

Marine animal-based omega-3 production is a mature but environmentally sensitive supply chain strongly driven by fuel use, catch efficiency, and co-product handling. Krill systems exhibit higher energy intensity and ecosystem risk than fish-based systems and should be modeled separately. Complementary indicators addressing stock depletion and marine ecosystem pressures can strengthen interpretation beyond traditional LCIA metrics.

3.2: Algae-Based Omega-3

Algae-based omega-3 production is a highly controlled, industrial process relying on engineered biological systems, traceable inputs, and energy-intensive downstream processing. Unlike fisheries- or agriculture-based supply chains, algae production allows decoupling from marine ecosystems and greater control over fatty acid product profile. However, these advantages introduce environmental tradeoffs that revolve around energy demand, feedstock sourcing, nutrient inputs and infrastructure intensity (Ahmad et al, 2022).

The methodological considerations described in the following sections are specific to algae-based omega-3 systems and supplements the general LCA guideline provided earlier.

3.2.1: System Boundary and Supply Chain Overview

Commercial omega-3 oils are overwhelmingly derived from lab-grown cultures of microalgae produced at large scale in industrial facilities. Producers typically begin with purified starter cultures grown in sterile inoculation systems, which stabilizes the lipid profile and reduces contamination risks. Wild-harvested algae are rarely used in modern product systems because their yields are inconsistent, oil profiles vary with season, and habitat, and harvesting at scale can present ecological and contaminant risks (Hilmarsdóttir et al., 2022).

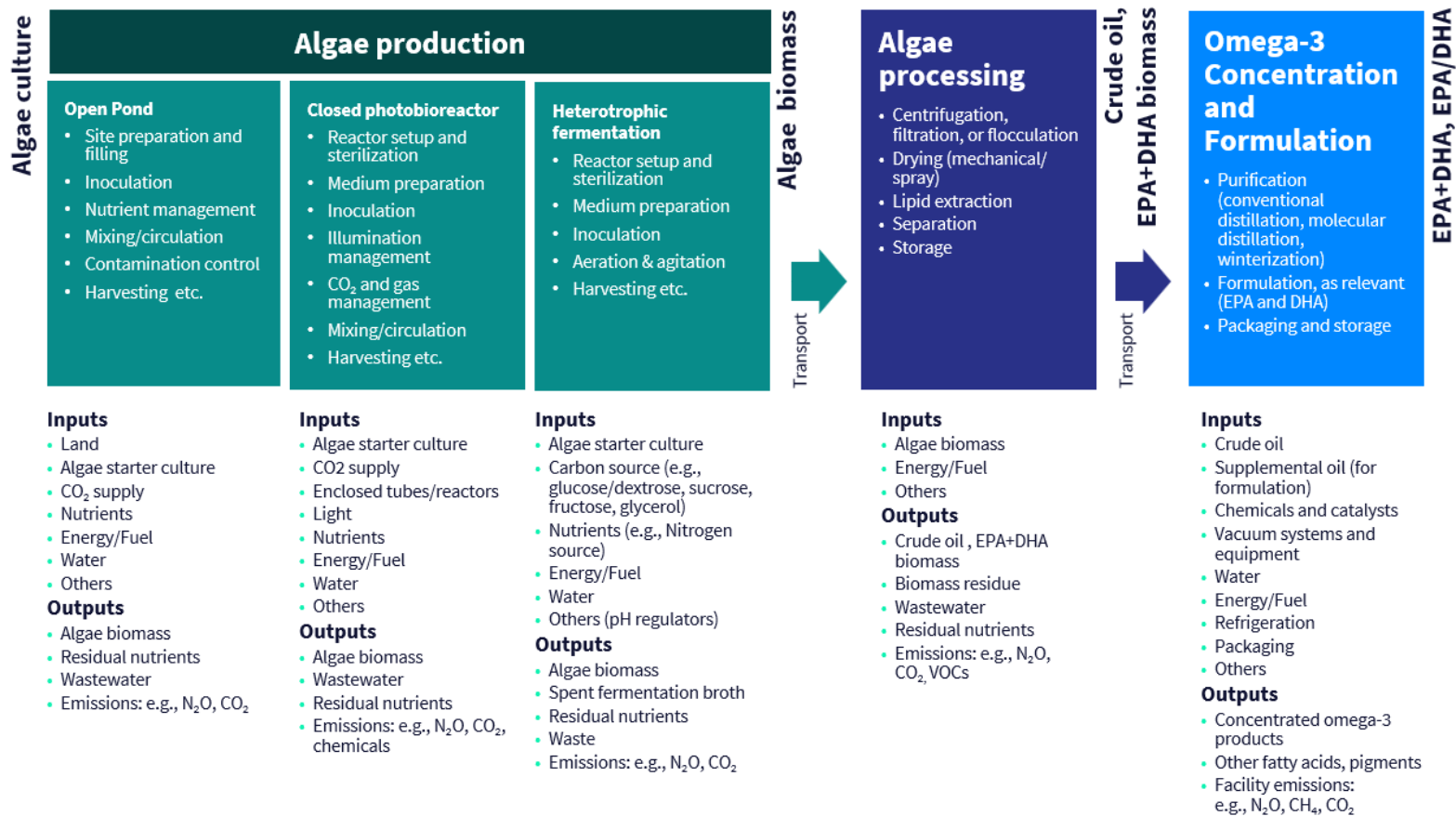
The typical cradle-to-gate system boundaries may include (Figure 6) below stages:

- Microalgae preparation and cultivation
- Carbon source
- Harvesting and biomass concentration
- Drying and cell disruption
- Lipid extraction and purification
- Omega-3 enrichment, concentration, packaging and storage (as applicable)

Figure 6 presents a high-level block flow diagram of the supply chain for algae-based omega-3 production. Individual stages, with some relevant activities are also shown; however these stages may be performed or owned by different entities along the value chain. The declared product shall reflect the modeled output (e.g., lipid extract, refined oil, DHA/EPA concentrate). Producers define their final products at different stages depending on the products' application (e.g., dried biomass, crude algal oil, refined DHA-, EPA-, or blended oils). If different from a cradle-to-gate omega-3 production study, the functional unit and system boundary shall reflect the final product form to ensure comparability across studies (McKuin et al., 2023; Porcelli et al., 2020; Qin et al., 2023; Schade et al., 2020; Braud et al., 2025).

Figure 6: Schematic Cradle-to-Gate System Boundary for Algae-Based Omega-3 Supply Chain

Each stage of omega-3 supply chain may not necessarily be operated by a single entity.



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- Informed by (Ahmad, et al., 2022; Brandi, et al., 2023 ; Davis, et al., 2021; Gaber, et al, 2022; Maiolo, et al., 2020 ; McKuin, et al., 2023; Parsons, et al., 2019; Porcelli, et al., 2020; Qin, et al., 2023; Togarcheti, et al., 2021; Wimmerova, et al., 2022; Zlaugotne, et al., 2023).

3.2.1.1: Cultivation Systems and Boundaries

Three principal cultivation routes are used in algae-based omega-3 production. These routes differ substantially in productivity, energy use, and dominant environmental drivers and shall be modeled separately.

Open Pond Systems

Open ponds are autotrophic, sunlight-driven systems with minimal infrastructure requirements. While electricity demand can be lower in closed systems, open ponds require large land areas and substantial water requirements and are highly susceptible to contamination. These limitations constrain lipid productivity and consistency, making the open ponds uncommon for high-DHA nutraceutical oils beyond pilot or demonstration scales. Key environmental drivers include land occupation, water scarcity, and low areal productivity. For photoautotrophic cultivation systems, carbon uptake occurs primarily through CO₂ assimilation during algal growth; CO₂ may be sourced from ambient air, industrial point-sources or on-site generation (e.g., from energy production). In LCA modeling, biogenic CO₂ uptake during cultivation and subsequent CO₂ release during downstream processing shall be treated consistently, with system boundaries clearly specifying whether the CO₂ is atmospheric or externally supplied (e.g., fossil-based or biogenic). These principles apply to both open pond and closed photobioreactor systems, with differences between them mainly in cultivation control, productivity, and energy requirements rather than in the fundamental carbon assimilation pathway.

Photobioreactors (PBRs)

Photobioreactors provide a controlled environment that reduces contamination and delivers uniform product quality. They can be deployed on non-arable land. Environmental impacts are driven primarily by embodied materials (e.g., glass, steel, plastics), electricity use for circulation and pressure losses, and, in some configurations, artificial lighting. While PBRs offer improved control, they are generally less competitive for high-volume DHA production due to cost and energy intensity. The same CO₂ sourcing considerations apply here as for open pond systems.

Heterotrophic Fermentation

Heterotrophic fermentation is the leading commercial route for nutraceutical-grade DHA. It achieves extremely high cell densities and operates year-round regardless of climate, providing precise control over fatty acid profiles. Environmental hotspots shift toward:

- Production of organic carbon sources (typically glucose or sucrose)
- Electricity for aeration, mixing, and temperature control
- Nutrient inputs (e.g., nitrogen and phosphorus)

Upstream glucose production (as the fermentation carbon source) frequently dominates climate change, land use, and eutrophication impacts. Any value chain-specific operational characteristics such as colocation with sugar mills, capturing fermentation offgas and biogenic CO₂ for use or sequestration, displacement of conventional energy through converting waste biomass from the operation to biomethane (Bartek et al., 2021), and integration with low-carbon energy systems (e.g., bagasse-fired combined heat & power) can materially influence results and should be explicitly modeled where applicable (Davis et al., 2021).

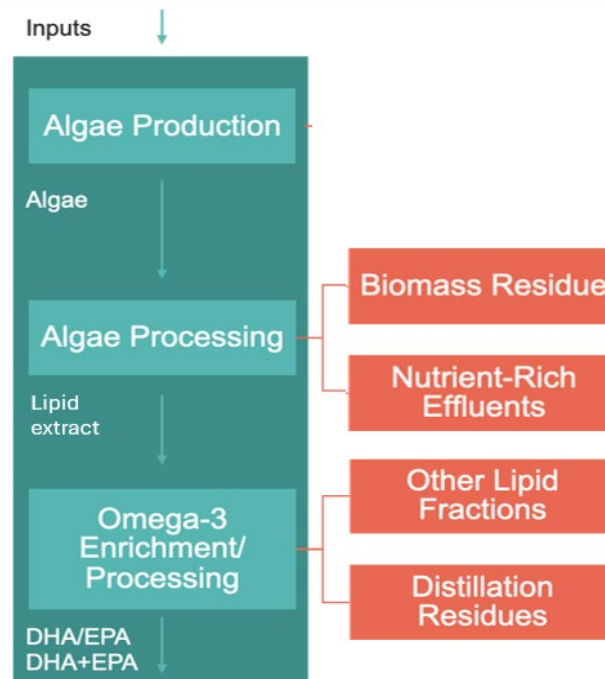
3.2.2: Methodological and Environmental Challenges

Recurring challenges in algae-based LCAs include:

- Limited traceability and variability in upstream sugar and nutrient datasets
- Inconsistent system boundary definitions across studies
- Allocation among high-value oils, residual biomass, and energy co-products (Figure 7)
- Treatment of waste-to-energy pathways and CO₂ handling

Inconsistent boundary or allocation choices are major barriers to comparability and should be justified and tested through sensitivity analysis, consistent with Section 2: Fundamentals of Life Cycle Assessment guidance.

Figure 7: Potential Allocation Points for Algae-Based Omega-3 Production



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3.2.3: Relevant Impact Categories

Impact categories of heightened relevance for algae-based omega-3 include:

- Climate change (e.g., electricity and glucose production),
- Land use and land use change (e.g., carbon source agriculture),
- Water use and scarcity (e.g., cultivation and processing),
- Eutrophication and ecotoxicity (e.g., nutrient inputs and runoff), and
- Resource use (e.g., infrastructure materials, solvents, nutrients).

Broad indicator coverage is recommended to avoid burden shifting between categories (McKuin et al., 2022; Togarcheti & Padamati, 2021). Table 3-C provides additional details on impact categories relevant to algae-based supply chain of omega-3 production and the contributing indicators.

Table 3-C: Major Impact Categories for Evaluating LCI of Algae-Based Omega-3 Product(s)

Impact Category*	Relevance Based on Emissions from Corresponding Stages of the Supply Chain
Climate Change	<i>PBR</i> high electricity demand for lighting, aeration, pumps, temperature control; <i>Heterotrophic</i> emissions from sugarcane or other feedstock cultivation for heterotrophic systems; CO ₂ emissions from extraction and refining.
Eutrophication	<i>Heterotrophic</i> upstream feedstock production impacts; <i>Phototrophic</i> nutrient-rich wastewater from algae cultivation and downstream processing; nitrogen/phosphorus leakage requiring energy intensive wastewater treatment
Land Use	Land occupation impacts linked to feedstock production (e.g. sugarcane farming for heterotrophic algae), and algae growth (e.g., open ponds) and supporting infrastructure
Water Use	High water demand for cooling towers, fermentation, and culture maintenance; wastewater management requirements
Resource Use	Energy-intensive cultivation systems, extraction operations, and manufacturing of specialized infrastructure (e.g., glass tubes, metal frames)
Photochemical Ozone Formation	VOC emissions during algae oil extraction and solvent handling contributing to ground-level ozone
Human Toxicity	Use of solvents, antifoam agents, pH regulators, and other chemical additives; exposure risks from wastewater discharges
Ecotoxicity	Leakage of nutrients and chemicals (e.g., biocides, additives) that can disrupt aquatic systems
Ozone Depletion	<i>Heterotrophic</i> refrigerant leakage from cooling systems associated with temperature-controlled algae cultivation (if applicable based on facility design)

*Impact categories are indicative only.

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3.2.4: Modeling and Sensitivity Guidance

Robust algae LCAs should include sensitivity analysis for:

- Carbon sourcing
- Process efficiency
- Energy mix assumptions
- Extraction and purification technologies
- Allocation approaches

Scenario analysis may explore renewable electricity usage, nutrient recycling, solvent-free extraction, and alternative feedstocks. Assumptions regarding CO₂ venting, or capture and energy recovery pathways should be clearly documented.

3.2.5: Summary

Algae-based omega-3 production represents a rapidly expanding, engineered supply chain with distinct environmental drivers centered on energy consumption, carbon and nutrient sourcing, and industrial infrastructure for open pond and phototrophic systems while the distinct environmental drivers for heterotrophic systems centered on the production of carbohydrates and energy consumption. Although algae systems avoid many marine ecological pressures associated with fish oil, they introduce trade-offs linked to industrial energy use, agricultural land transformation, and large-scale infrastructure. Credible, comparable LCAs depend on primary data, clear product and boundary definitions, consistent and justified allocation procedures, and scenario analysis that reflect regional conditions and emerging technologies. Harmonized application of these principles supports transparent sustainability reporting and meaningful comparison across omega-3 sources.

3.3: Oilseed-Based Omega-3

Seed-based omega-3 systems are derived from oilseed crops engineered to produce EPA and/or DHA and are inherently linked to agricultural systems. This section defines supply-chain characteristics and methodological requirements specific to oilseed-based pathways, supplementing the general LCA guidance in Section 2: Fundamentals of Life Cycle Assessment.

Compared with marine pathways, oilseed-based omega-3 production is typically more dependent on agricultural practices, regional conditions, and process maturity (Moeller et al., 2017; Pelletier et al., 2008). Primary data availability is often limited to pilot or early commercial facilities, requiring modeled inventories and careful scenario analysis.

3.3.1: System Boundary

The cradle-to-gate system boundary for oilseed-based omega-3 production can include:

- Oilseed, e.g., canola cultivation and harvesting, including fertilizers, water, and energy inputs, as well as any field emissions to the agroecosystem,
- Seed crushing, mechanical or solvent-based oil extraction, and refining, and
- Omega-3 enrichment, concentration, packaging and storage (as applicable).

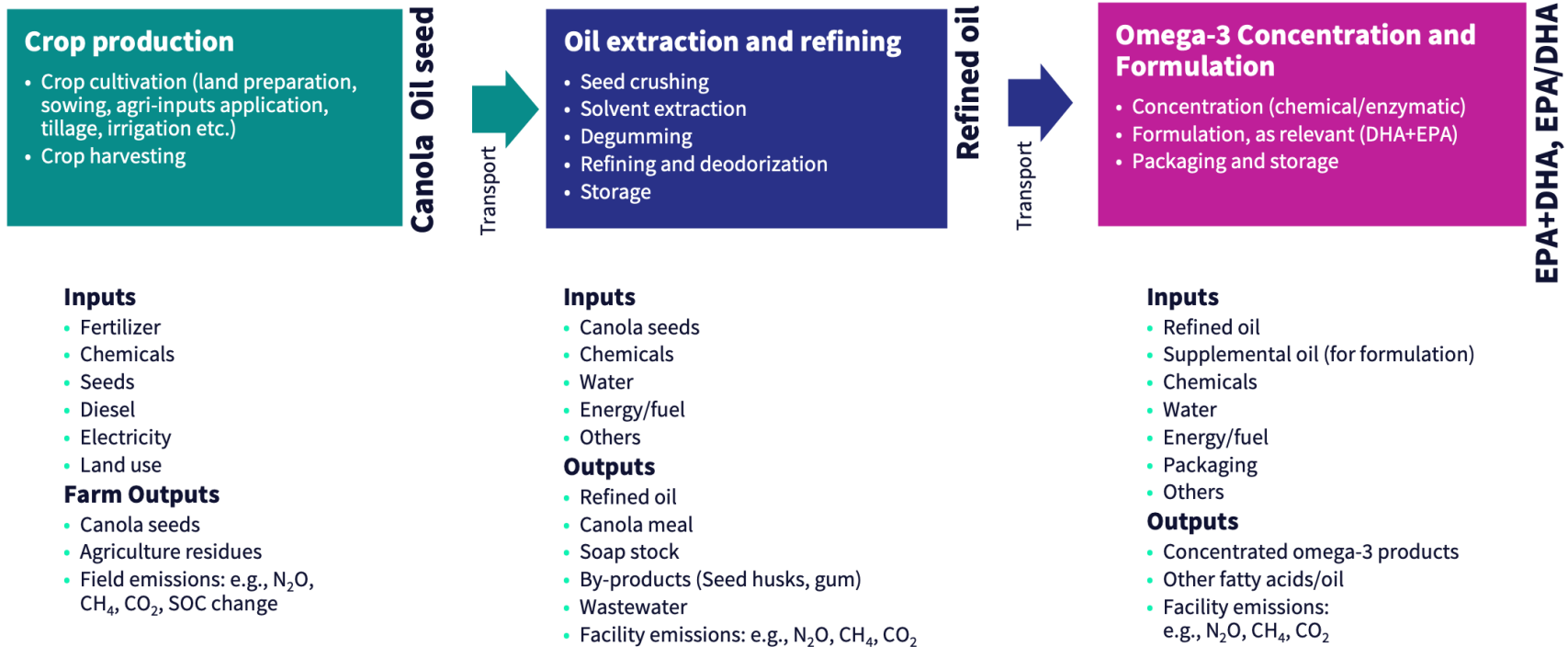
Distribution, retail, and consumer use may be excluded unless explicitly required by the study goal.

The declared product shall reflect the modeled output (e.g., crude oil, refined oil, DHA/EPA concentrate). If intermediate products are purchased (crude oil from other sources), upstream agricultural and processing stages shall be included or justified if excluded.

Figure 8 presents a high-level block flow diagram of the supply chain for oil seed-based omega-3 production. Individual stages, with some relevant activities are also shown; however these stages may be performed or owned by different entities along the value chain. The system boundary encompasses all processes from canola cultivation to the production and packaging of omega-3 enriched products. It includes upstream agricultural activities, midstream oil extraction and refining, and downstream enrichment and formulation stages.

Figure 8: Schematic Cradle-to-Gate System Boundary for Oilseed-Based Omega-3 Supply Chain

Each stage of omega-3 supply chain may not necessarily be operated by a single entity.



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- Informed by (Moeller et al. 2017 ; MacIntosh et al., 2021; Ukaew et al., 2016; Pelletier et al., 2008 ; Sieverding et al., 2016)

3.3.2: Oilseed-Based Omega-3 Production Overview

Oilseed-based omega-3 production is an emerging pathway, typically using genetically modified oilseed crops (e.g., canola) engineered to produce EPA and/or DHA. This system exhibits high variability and dependence on agricultural practices, regional conditions, and process maturity. Primary data availability is often limited to pilot or early commercial facilities, and modeled inventories are commonly required (MacIntosh et al., 2021).

Key environmental drivers for this supply chain include:

- Land occupation and land-use change, which influence carbon stocks, biodiversity pressure, and yield-related impact intensities.
- Nitrogen fertilizer use and soil emissions during crop cultivation, which dominate climate change, eutrophication, and acidification impacts through nitrous oxide (N₂O), ammonia (NH₃), and nitrate losses, as relevant.
- Crop yield and omega-3 content variability, driven by genotype, climate, and agronomic practices, which directly affect impacts per unit of EPA/DHA produced.
- Energy use in oil extraction, refining, and omega-3 enrichment, particularly for solvent recovery, deodorization, and concentration steps.
- Co-product handling (e.g., canola meal, other fatty acids).
- Water use (depending on local conditions).

Unlike marine systems, environmental performance of oilseed-based omega-3 is strongly shaped by site-specific agronomy (fertilizer rates, tillage, irrigation, crop rotation) and regional climate and soil conditions, which can cause large spatial and temporal variability in results (MacWilliam et al., 2016; Queiros et al., 2015; Ukaew et al., 2016; Sieverding et al., 2016; Pelletier et al., 2008). Therefore, regionalized data and scenario-based modeling are particularly important for credible assessments.

3.3.3: Methodological and Environmental Challenges

Oilseed-based omega-3 LCAs face several methodological challenges that can materially influence results, as can be seen in the following sections.

3.3.3.1: Soil Emissions and SOC Changes

Field emissions may be quantified using site-specific measurements or process-based models that represent local farming conditions. Key agricultural practices, including tillage, fertilizer application, crop rotation, and irrigation, strongly influence GHG emissions and overall environmental performance. Tillage affects soil carbon and fuel use. Conventional tillage increases CO₂ emissions and accelerates soil organic carbon (SOC) loss while reduced-till or no-till systems help maintain SOC and lower fuel-related emissions. Nitrogen fertilizer management is a major driver of N₂O emissions and precision application based on soil testing can reduce excess input. Crop rotation influences fertilizer demand and pest pressure, and diversified rotations improve soil health and lower synthetic input requirements. Irrigation increases energy and water use compared to rainfed systems.

Soil emissions (N_2O , CH_4 , CO_2) are highly sensitive to the modeling approach used for nitrogen-related pathways (N_2O , NH_3 volatilization, and nitrate leaching) and SOC changes. The IPCC Guidelines (2006, 2019) provide methods with increasing levels of detail, ranging from default approaches to country- and farm-specific methods, to quantify field-level direct and indirect emissions resulting from the application of farm inputs. An example of country-specific factors includes emission factors for various direct and indirect GHG emissions from soil as suggested in USDA guideline (Hanson et al., 2024). These approaches help to quantify field emissions due to fertilizer, crop residues, and soil organic matter changes, or alternatively, process-based models that represent the specific farm management conditions and agro-climates may be used.

3.3.3.2: Crop Rotation Effects

Omega-3 seed crops like canola are generally grown within multi-year rotations, and their environmental impacts depend on long-term soil, nutrient, and pest dynamics (Ukaew et al., 2016; Pelletier et al., 2008). These effects cannot be captured within a single season, leading to overlooked cross-rotation impacts such as nitrogen carryover from legumes or increased pesticide requirements due to pest buildup. Although currently available methods apply nutrient credits or burden allocations, there is a lack of indirect effects like SOC changes and long-term productivity shifts. This can lead to bias results and encourage unsustainable practices, such as excessive residue removal that harms soil health. When full rotation modeling is not feasible, impacts may be allocated across rotation crops based on area or time, with transparent documentation of assumptions and limitations (Costa et al., 2020). Furthermore, scenario and sensitivity analyses can be applied to test the influence of nitrogen carryover, residue management, and pest pressure during such rotations.

3.3.3.3: Spatial and Temporal Variability

Crop production systems vary significantly across regions due to differences in soil type, climate, topography, and management practices. Spatial variability affects factors such as fertilizer requirements, irrigation needs, and yield potential, which in turn influence GHG emissions and resource use (MacWilliam et al., 2016; Queiros et al., 2015; Ukaew et al., 2016). For example, canola grown in a semi-arid region may require supplemental irrigation and might have lower yields compared to canola grown in temperate zones. As a result, the semi-arid-sourced product may have higher emissions per unit.

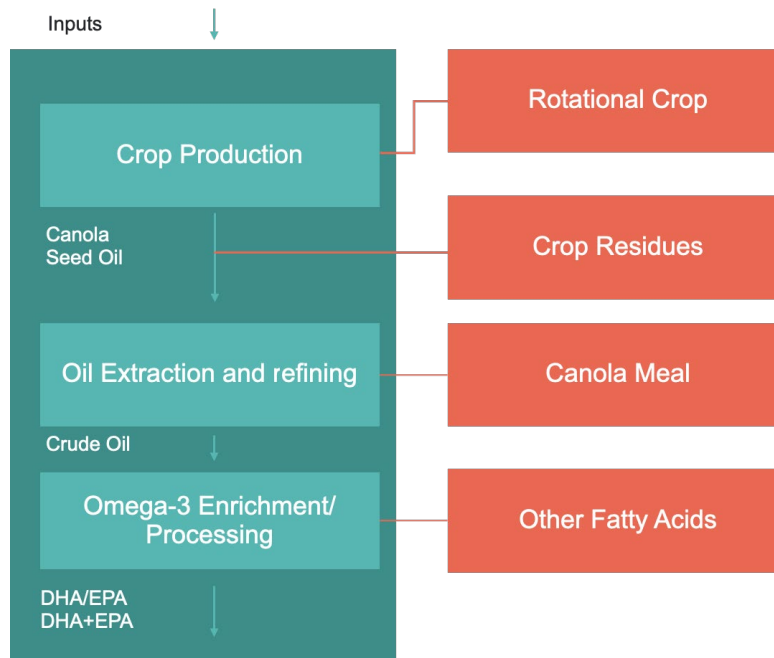
Similarly, temporal variability that arises from year-to-year changes in weather conditions, pest pressure, and technological improvements can alter input use and productivity over time. Practitioners can adopt several approaches when incorporating these variations into an LCA. For example, regionalized inventory data should be used instead of generic averages, leveraging geospatial datasets and agricultural statistics to reflect local conditions. An uncertainty analysis should also be applied to account for variability that cannot be fully modeled, ensuring transparency in results and recommendations.

3.3.3.4: Handling Multiple Products

Oil extraction produces crude canola oil alongside valuable co-products such as canola meal (Requena et al., 2011; Dalgaard et al., 2008) (Figure 9). Because these co-products have market value, proper allocation or, preferably, system expansion is required to avoid biased results. Under system expansion, canola meal is credited for displacing conventional protein

feeds (e.g., soybean meal), and separated fatty acids from omega-3 enrichment are credited for replacing equivalent market products. These avoided burdens reduce the net impacts assigned to canola oil and DHA/EPA omega-3. Using inconsistent methods to account for these multiple products can distort results, as discussed in Section 2: Fundamentals of Life Cycle Assessment.

Figure 9: Procedures and Potential Allocation Points for Oilseed-Based Omega-3 Production



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3.3.4: Relevant Impact Categories

Impact category selection for an LCA of oilseed-derived omega-3 should reflect the processes that most influence environmental outcomes and the intended study scope. Key drivers include:

- Fertilizer use and soil N₂O emissions during cultivation (i.e., affecting climate change, eutrophication, and acidification),
- Energy use in oil extraction, refining, and omega-3 enrichment (i.e., driving fossil resource use and GHG emissions), and
- Land and water use (i.e., influencing biodiversity, soil quality, and water scarcity).

Secondary contributors such as pesticides, solvents, transport, and packaging may affect toxicity-related categories and photochemical ozone formation. The chosen categories should align with regulatory needs, sustainability reporting goals, or the desired level of environmental detail. Table 3-D shows how each impact category can be linked to respective primary emission sources across life cycle stages.

Table 3-D: Major Impact Categories for Evaluating LCI of Oilseed-Based Omega-3 Product(s)

Impact Category*	Relevance Based on Emissions from Corresponding Stages of the Supply Chain
Climate Change	Fertilizer use, soil N ₂ O, processing energy
Eutrophication	Nutrient runoff and leaching from the agricultural step
Acidification	NH ₃ and NO _x emissions mainly from the agricultural step
Land Use	Crop area occupation, soil carbon loss
Water Use	Irrigation, seed/oil processing
Resource Use	Energy consumption in refining, refrigeration, transport
Photochemical Ozone Formation	Transport, solvent use
Human/Ecotoxicity	Pesticides, fertilizers and other solvents
Ozone Depletion	Refrigerant leakage

*Impact categories are indicative only.

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3.3.5: Summary

Oilseed-based omega-3 production is an emerging, land-based pathway with environmental performance dominated by agricultural emissions, land and water use, energy demand, and co-product handling. Results are highly sensitive to agronomic practices, soil modeling choices, yield assumptions, and allocation methods.

Credible LCAs of oilseed-based omega-3 therefore require regionalized inventories, transparent treatment of co-products, sensitivity and scenario analysis, and explicit consideration of technology maturity. These practices are essential to ensure fair comparison with marine and algal omega-3 pathways in order to support responsible sustainability claims.

Section 4: Guidance for Stakeholders

4.1: Methodological Principles for Application

This guideline is intended to support consistent, credible, and comparable LCAs across diverse omega-3 production pathways. When applying the guideline, users should adhere to the following principles:

1. Pathway-specific modeling is essential.

Omega-3 supply chains differ fundamentally in their environmental drivers. Results are only meaningful when system boundaries, data sources, and assumptions reflect the specific production route.

2. Nutritional function should define the functional unit.

Mass-based functional units based on EPA, DHA, or EPA+DHA better represent product function and improve comparability across pathways.

3. Multi-output systems must be treated transparently.

Allocation choices strongly influence results and shall follow the ISO hierarchy, be clearly justified, and be tested through sensitivity analysis.

4. Variability and uncertainty shall be explicitly addressed.

Spatial, temporal, and technological variability must be reflected through regional data, scenarios, and uncertainty analysis rather than single deterministic values.

5. Downstream processing cannot be treated as marginal.

Refining, concentration, and purification steps are material contributors across all pathways and must be modeled with equal rigor.

6. Comparability depends on consistency.

Harmonized system boundaries, functional units, allocation rules, and impact categories are required to avoid methodological bias.

7. Interpretation must respect methodological limits.

LCA results should be used to identify hotspots and improvement opportunities, not as absolute performance rankings, unless methodological equivalence is demonstrated.

References

- Ahmad, A., W. Hassan, S., & Banat, F. (2022). An overview of microalgae biomass as a sustainable aquaculture feed ingredient: Food security and circular economy. *Bioengineered*, 13(4), 9521–9547. <https://doi.org/10.1080/21655979.2022.2084495>
- Ardente, F., & Cellura, M. (2012). Economic allocation in life cycle assessment: the state of the art and discussion of examples. *Journal of Industrial Ecology*, 16(3), 387-398. <https://doi.org/10.1111/j.1530-9290.2011.00434.x>
- Bare, J. C. (2002). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *Journal of industrial ecology*, 6(3-4), 49-78. <https://doi.org/10.1162/108819802766269539>Digital Object Identifier (DOI)
- Bartek, L., Strid, I., Henryson, K., Junne, S., Rasi, S., & Eriksson, M. (2021). Life cycle assessment of fish oil substitute produced by microalgae using food waste. *Sustainable Production and Consumption*, 27, 2002–2021. <https://doi.org/10.1016/j.spc.2021.05.021>
- Bashiri, B., Crobotova, J., Kvangarsnes, K., Gavrilova, O., & Vilu, R. (2024). Environmental and economic life cycle assessment of enzymatic hydrolysis-based fish protein and oil extraction. *Resources*, 13(5), 61. <https://doi.org/10.3390/resources13050061>
- Bimbo, A.P. Fishmeal and oil. In: *Marine & Freshwater Products Handbook*, pp. 541-581 (2000).
- Bimbo, A.P. (2019). *Marine Oils*. International Fisheries Technology, Post Office Box 1606, 55 Cedar Lane, Kilmarnock, Virginia, USA 22482-1606. https://www.aocs.org/resource/marine-oils/?utm_source (Accessed 01/23/2026)
- Brandi, M., Kapuscinski, A. R., Sarker, P. K., Nicolette, C., Lim, J., & Martin, S. (2023). Comparative life cycle assessment of marine microalgae, *Nannochloropsis* sp. and fishmeal for sustainable protein ingredients in aquaculture feeds. *Elementa*, 11(1). <https://doi.org/10.1525/elementa.00083>
- Braud, L., Rodriguez, J. G., Rajaonison, A., Schelte, N., Mangini, S., Bernard, O., ... & Unamunzaga, C. (2025). Life cycle assessment of algal products: A step-by-step guide to application (Doctoral dissertation, European Algae Biomass Association).
- Brown, E., Vázquez Rowe, I., Ulrich, C., Asselin, A.-C., Casonato, C. et al., Exploring environmental impact methodologies to quantify fish stock exploitation and seabed impacts of fishing - Evaluating LCA and Non-LCA Approaches, Publications Office of the European Union, Luxembourg, 2025, <https://data.europa.eu/doi/10.2760/7365767>, JRC142085.
- Calder, P. C. (2015). Functional roles of fatty acids and their effects on human health. *Journal of Parenteral and Enteral Nutrition*, 39(1_suppl), 18S–32S. <https://doi.org/10.1177/0148607115595980>
- Cantillo, J., Deshpande, P. C., & Jafarzadeh, S. (2025). Life cycle assessment of *Calanus finmarchicus* products. *The International Journal of Life Cycle Assessment*, 30(3), 511–524. <https://doi.org/10.1007/s11367-024-02643-7>
- Ciroth, A., Muller, S., Weidema, B., & Lesage, P. (2016). Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *The International Journal of Life Cycle Assessment*, 21(9), 1338-1348. <https://doi.org/10.1007/s11367-013-0670-5>
- Costa, M. P., Chadwick, D., Saget, S., Rees, R. M., Williams, M., & Styles, D. (2020). Representing crop rotations in life cycle assessment: a review of legume LCA studies. *The*

International Journal of Life Cycle Assessment, 25(10), 1942-1956. <https://doi.org/10.1007/s11367-020-01812-x>

Dalgaard, R., Schmidt, J., Halberg, N., Christensen, P., Thrane, M., & Pengue, W. A. (2008). LCA of soybean meal. The International Journal of Life Cycle Assessment, 13(3), 240-254. <https://doi.org/10.1065/lca2007.06.342>

Davis, D., Morão, A., Johnson, J. K., & Shen, L. (2021). Life cycle assessment of heterotrophic algae omega-3. Algal Research, 60, 102494. <https://doi.org/10.1016/j.algal.2021.102494>

Deville, A., Vázquez-Rowe, I., Avadi, A., Miranda, F., & Kahhat, R. (2025). Identifying current trends in the environmental impacts linked to fishmeal and fish oil production in Peru.

ecoinvent (2023). ecoinvent database version 3.10 (Life cycle inventory database). ecoinvent Association. <https://www.ecoinvent.org>

EC (2010). *International reference life cycle data system (ILCD) handbook: General guide for life cycle assessment—Detailed guidance* (First ed., EUR 24708 EN). European Commission, Joint Research Centre, Institute for Environment and Sustainability. Publications Office of the European Union.

European Pet Food Industry Federation (FEDIAF). (2025). *Product Environmental Footprint Category Rules (PEFCR) for pet food*. [Product Environmental Footprint Category Rules \(PEFCR\) | FEDIAF](#) (Accessed 04/02/2026). FAO. The Production of Fishmeal and Oil. FAO Fisheries Technical Paper 142 rev. 1. 63 pp. Food and Agriculture Organization of the UN Rome Italy (1986).

FAO. <https://www.fao.org/fishery/en> (2011). (Accessed 01/23/2026)

FEFAC (2025). *Product Environmental Footprint Category Rules (PEFCR) — Feed for food-producing animals* (Final PEFCRs update 10 February 2025). FEFAC, European Feed Manufacturers Federation. [PEFCR Feed_FinalPEFCRs-update-10-02-2025.pdf](#) (Accessed 04/02/2026)

Frischknecht, R., Krebs, L., Dinkel, F., Kägi, T., Stettler, C., Zschokke, M., Braunschweig, A., Ahmadi, M., Itten, R. & Stucki, M. (2021). Ökofaktoren Schweiz 2021 gemäss der Methode der ökologischen Knappheit. Methodische Grundlagen und Anwendung auf die Schweiz. Umwelt-Wissen no. 2121. Bundesamt für Umwelt BAFU, Öbu. www.bafu.admin.ch/uw-2121-d

Frischknecht Rolf, Steiner Roland, Jungbluth Niels 2009: The Ecological Scarcity Method – Eco-Factors 2006. A method for impact assessment in LCA. Environmental studies no. 0906. Federal Office for the Environment, Bern: 188 pp.

Gaber, K., Rösch, C., & Biondi, N. (2022). Life cycle assessment of total fatty acid (TFA) production from microalgae *nannochloropsis oceanica* at different sites and under different sustainability scenarios. BioEnergy Research, 15(3), 1595-1615. <https://doi.org/10.1007/s12155-021-10279-z>

Guinée, J. B., Heijungs, R., & Huppes, G. (2004). Economic allocation: examples and derived decision tree. The international journal of life cycle assessment, 9(1), 23-33. <https://doi.org/10.1007/BF02978533>

Hélias, A. Addressing fisheries in environmental footprint assessments, how and why?. Int J Life Cycle Assess 30, 2565–2568 (2025). <https://doi.org/10.1007/s11367-025-02519-7>

Hilmarsdóttir, G. S., Ögmundarson, Ó., Arason, S., & Gudjónsdóttir, M. (2022). Identification of environmental hotspots in fishmeal and fish oil production towards the optimization of energy-

related processes. *Journal of Cleaner Production*, 343, 130880.

<https://doi.org/10.1016/j.jclepro.2022.130880>

Huijbregts, M. A. J., Steinmann, Z. J. N., Elshout, P. M. F., Stam, G., Verones, F., Vieira, M. D. M., ... van Zelm, R. (2016). ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level (RIVM Report 2016-0104). National Institute for Public Health and the Environment. <https://www.rivm.nl/bibliotheek/rapporten/2016-0104.html>

IPCC. (2006). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies (IGES). <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>

IPCC. (2019). 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. <https://www.ipcc-nggip.iges.or.jp/public/2019rf/>

IPCC. (2021). *Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, ... & B. Zhou, Eds.). Cambridge University Press. <https://doi.org/10.1017/9781009157896>

Kristinsson, H. Value added utilization of seafood processing by-products. Paper presented at the 2010 Atlantic Fisheries Technology Conference, St. Johns Newfoundland (2010).

MacIntosh, S. C., Shaw, M., Connelly, M., & Yao, Z. J. (2021). Food and feed safety of NS-B5ØØ27-4 omega-3 canola (*Brassica napus*): A new source of long-chain omega-3 fatty acids. *Frontiers in Nutrition*, 8, 716659. <https://doi.org/10.3389/fnut.2021.716659>

MacWilliam, S., Sanscartier, D., Lemke, R., Wismer, M., & Baron, V. (2016). Environmental benefits of canola production in 2010 compared to 1990: A life cycle perspective. *Agricultural Systems*, 145, 106-115. <https://doi.org/10.1016/j.agsy.2016.03.006>

Maiolo, S., Parisi, G., Biondi, N., Lunelli, F., Tibaldi, E., & Pastres, R. (2020). Fishmeal partial substitution within aquafeed formulations: life cycle assessment of four alternative protein sources. *The international journal of life cycle assessment*, 25(8), 1455-1471.

Margni, M., Gloria, T., Bare, J., Seppälä, J., Steen, B., Struijs, J., ... & Jolliet, O. (2008). Guidance on how to move from current practice to recommended practice in life cycle impact assessment (Unpublished guidance document). UNEP-SETAC Life Cycle Initiative.

McKuin, B., Kapuscinski, A. R., Sarker, P. K., Cheek, N., Lim, J., & Sabarsky, M. (2023). Comparative life cycle assessment of marine microalgae, *Nannochloropsis* sp. and fishmeal for sustainable protein ingredients in aquaculture feeds. *Elem Sci Anth*, 11(1), 00083. <https://doi.org/10.1525/elementa.00083>

Mérieux NutriSciences | Blonk Consultants. (2023). Agri-footprint life cycle inventory database, version 7.0. <https://www.agri-footprint.com> (Accessed 01/23/2026)

Moeller, D., Sieverding, H. L., & Stone, J. J. (2017). Comparative farm-gate life cycle assessment of oilseed feedstocks in the Northern Great Plains. *BioPhysical Economics and Resource Quality*, 2(4), 13. <https://doi.org/10.1007/s41247-017-0020-x>

Newton, R. W., Maiolo, S., Malcorps, W., & Little, D. C. (2023). Life cycle inventories of marine ingredients. *Aquaculture*, 565, 739096. <https://doi.org/10.1016/j.aquaculture.2023.739096>

NOAA Fisheries. Feeds for Aquaculture | NOAA Fisheries. (Accessed 01/23/2026)

Parker, R. W. R., & Tyedmers, P. H. (2012). Life cycle environmental impacts of three products derived from wild-caught Antarctic krill (*Euphausia superba*). *Environmental Science & Technology*, 46(9), 4958–4965. <https://doi.org/10.1021/es2040703>

Parajuli, R., Knudsen, M. T., Birkved, M., Djomo, S. N., Corona, A., & Dalgaard, T. (2017). Environmental impacts of producing bioethanol and biobased lactic acid from standalone and integrated biorefineries using a consequential and an attributional life cycle assessment approach. *Science of the Total Environment*, 598, 497-512.

Parsons, S., Allen, M. J., Abeln, F., McManus, M., & Chuck, C. J. (2019). Sustainability and life cycle assessment (LCA) of macroalgae-derived single cell oils. *Journal of Cleaner Production*, 232, 1272-1281. <https://doi.org/10.1016/j.jclepro.2019.05.315>

Pelletier, N., Arsenault, N., & Tyedmers, P. (2008). Scenario modeling potential eco-efficiency gains from a transition to organic agriculture: life cycle perspectives on Canadian canola, corn, soy, and wheat production. *Environmental management*, 42(6), 989-1001. <https://doi.org/10.1007/s00267-008-9155-x>

Porcelli, R., Dotto, F., Pezzolesi, L., Marazza, D., Greggio, N., & Righi, S. (2020). Comparative life cycle assessment of microalgae cultivation for non-energy purposes using different carbon dioxide sources. *Science of the Total Environment*, 721, 137714. <https://doi.org/10.1016/j.scitotenv.2020.137714>

Qin, Z. H., Hu, X., Mou, J. H., He, G. H., Ye, G. B., Li, H. Y., ... & Wang, X. (2023). Environmental profiling microalgae-based eicosapentaenoic acid production along the technical advancement via life cycle assessment. *Journal of Cleaner Production*, 397, 136477. <https://doi.org/10.1016/j.jclepro.2023.136477>

Queiros, J., Malca, J., & Freire, F. (2015). Environmental life cycle assessment of rapeseed produced in Central Europe: addressing alternative fertilization and management practices. *Journal of Cleaner Production*, 99, 266-274. <https://doi.org/10.1016/j.jclepro.2015.03.016>

Requena, J. S., Guimaraes, A. C., Alpera, S. Q., Gangas, E. R., Hernandez-Navarro, S., Gracia, L. N., ... & Cuesta, H. F. (2011). Life Cycle Assessment (LCA) of the biofuel production process from sunflower oil, rapeseed oil and soybean oil. *Fuel Processing Technology*, 92(2), 190-199. <https://doi.org/10.1016/j.fuproc.2010.03.004>

Rohman, A., Irnawati, Windarsih, A., Riswanto, F. D. O., Indrayanto, G., Fadzillah, N. A., ... & Bakar, N. K. A. (2023). Application of chromatographic and spectroscopic-based methods for analysis of Omega-3 (Ω -3 Fas) and Omega-6 (Ω -6 Fas) fatty acids in marine natural products. *Molecules*, 28(14), 5524. <https://doi.org/10.3390/molecules28145524>

Schade, S., Stangl, G. I., & Meier, T. (2020). Distinct microalgae species for food—Part 2: Comparative life cycle assessment of microalgae and fish for eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and protein. *Journal of Applied Phycology*, 32(5). <https://doi.org/10.1007/s10811-020-02181-6>

Sieverding, H. L., Zhao, X., Wei, L., & Stone, J. J. (2016). Life-cycle assessment of oilseeds for biojet production using localized cold-press extraction. *Journal of environmental quality*, 45(3), 967-976. <https://doi.org/10.2134/jeq2015.06.0313>

Sphera Solutions GmbH. (2023). Sphera managed LCA content database (formerly GaBi databases). Sphera. <https://lcadatabase.sphera.com>

- Swanson, D., Block, R., & Mousa, S. A. (2012). Omega-3 fatty acids EPA and DHA: Health benefits throughout life. *Advances in Nutrition*, 3(1), 1–7. <https://doi.org/10.3945/an.111.000893>
- Togarcheti, S. C., & Padamati, R. B. (2021). Comparative life cycle assessment of EPA and DHA production from microalgae and farmed fish. *Clean Technologies*, 3(4). <https://doi.org/10.3390/cleantechnol3040042>
- Ukaew, S., Shi, R., Lee, J. H., Archer, D. W., Pearlson, M., Lewis, K. C., ... & Shonnard, D. R. (2016). Full chain life cycle assessment of greenhouse gases and energy demand for canola-derived jet fuel in North Dakota, United States. *ACS Sustainable Chemistry & Engineering*, 4(5), 2771-2779. <https://doi.org/10.1021/acssuschemeng.6b00276>
- USEtox Documentation Team. (2017/updated). USEtox® 2.0 documentation [Documentation of the scientific consensus model for characterizing human and ecotoxicological impacts of chemical emissions in life cycle assessment]. USEtox. <https://usetox.org/model/documentation>
- USLCI, National Renewable Energy Laboratory. (2024). U.S. Life Cycle Inventory (USLCI) database. U.S. Department of Energy. <https://www.nrel.gov/analysis/lci.html>
- Wimmerova, L., Keken, Z., Solcova, O., & Vavrova, K. (2022). A comparative analysis of environmental impacts of operational phases of three selected microalgal cultivation systems. *Sustainability*, 15(1), 769. <https://doi.org/10.3390/su15010769>
- Zhang, X., Kotin, A., Zgola, M., & Genuine Alaska Pollock Producers. (2021). Life cycle assessment of wild Alaska pollock final ISO LCA report. <https://www.alaskapollock.org/media/2246/final-report.pdf> (Accessed 06/10/2025)
- Zlaugotne, B., Diaz Sanchez, F., Pubule, J., & Blumberga, D. (2023). Life cycle assessment of fish feed for oil alternatives-environmental impact of microalgae, rapeseed and fish oil. <https://doi.org/10.15159/AR.23.074>

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